# EVALUATION OF ENERGY EFFICIENCY, INDOOR AIR QUALITY AND SUSTAINABILITY TESTING OF GREEN BUILDINGS IN NAIROBI, KENYA

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# Evaluation of Energy Efficiency, Indoor Air Quality and Sustainability Testing of Green Buildings in Nairobi, Kenya

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**A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science in Energy Technology of Jomo Kenyatta University of Agriculture and Technology**

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# DECLARATION

This thesis is my original work and has not been submitted for the award of a degree in any other University

Signature…………………………………………………Date………………………...

**Mulei David Nzioka**

This thesis has been submitted for examination with our approval as University supervisors.

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# DEDICATION

This thesis is dedicated to my family, my wife and daughter for the invaluable support and understanding during the period of study.

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# ABBREVIATIONS

$CO_2$ - Carbon dioxide

CUEA - Catholic University of Eastern Africa

DOE - Department of Energy

EPBD - Energy Performance of Building Directive

ESCOs - Energy Service Companies

EU - European Union

ERC - Energy Regulation Commission

GHG - Greenhouse gas

GoK - Government of Kenya

HVACs - Heating, ventilation and air conditioning systems

NCCRS - National Climate Change Rsponse Strategy

NZEBs - Net Zero Energy Buildings

PCM - Phase Changing Materials

PV - Photovoltaic

GBT - Green Building Technology

GAF - Green Africa Foundation

LECRD - Low Emission and Climate Resilient Development

LEED - Leadership in Energy and Environmental Design

MoE - Ministry of Energy

USAID - United States Agency for International Development

UNDP - United Nations Development Program

PPA - Power Purchase Agreement

IDP - Independent Power Producers

VOC - Volatile Organic Compounds

Sf - Square feet

# ABSTRACT

Green buildings should save energy, be environmentally friendly and offer healthy and safe indoor conditions for the occupants. To reduce energy consumption and improve indoor air quality in buildings require innovative ways. The study aimed to establish green buildings' impact on energy efficiency and indoor health environment. Four buildings, two green (GB1 and GB2), and two non-green (NGB1 and NGB2) at Strathmore University and CUEA were used. Energy efficiency was investigated using power bills from Kenya Power for the year 2018 whereas buildings air change rates were determined using metabolic $CO_2$ as a tracer gas and using the tracer gas method to calculate the air change rate. $CO_2$ concentrations were monitored over a period of 4 months using HT-2000 $CO_2$ meters. Checklists by GreenMark Standard were used to assess the green buildings' energy and indoor health environment sustainability. The results show statistical significant difference in energy consumption between green and non-green buildings (p-value= $1.18\times10^{-12}$) as the green buildings consume 40% less energy. Green buildings had between 80% to 86% better air change rates than non-green buildings. An indication that the probability to inhale contaminated air was higher than 0.8 in non-green buildings. There was significance difference in air change rate between green and non-green buildings (p-value=0.02 for buildings at Strathmore University; p-value= 0.002 for buildings at CUEA). Using the GreenMark checklist, GB1 scored 68% whereas GB2 scored 85% for health indoor environment category. For Energy efficiency category, GB1 scored 87.5% while GB2 scored 50%. Therefore, policy on green building technology should be developed by government and construction sector to reap the energy efficiency and quality indoor environment benefits

# CHAPTER ONE

# INTRODUCTION

## 1.1 Background of Study

Buildings utilize energy mostly for space heating, cooling and lighting. Lighting, heating and cooling energy costs and amounts in a particular building depend on the design criteria of the buildings (Akadiri *et al.*, 2012). Building energy efficiency refers to energy consumption per square meter of floor area a building compared to a benchmarked value in a country. Green buildings should minimize energy usage per unit area of the building contributing to energy efficiency improvement (Chel and Kaushik, 2018). Green building design consider efficient resource use such as water, material and energy, while minimizing the impact the buildings would have on environment from design, siting, operation, construction, maintenance stages and during possible renovations in future (Lee, 2013). Inefficient resource consumption, poor indoor air quality and greenhouse gases emissions are the major motivations towards adoption of green buildings. Buildings consume between 30% and 40% of the total energy produced globally (Howe, 2010). Excessive use of fossil fuels to power buildings and industries result in environmental degradation due to the emission of greenhouse gases, while foreign exchange incurred in importing crude oil to the country is high (Omer, 2011). Hydropower in the country is not fully reliable due to recurrent droughts in Kenya, hence the need to improve energy efficiency and reduce overreliance on utility power.

Nairobi County, Kenya is located along the equator with climatic conditions that qualify for natural ventilation systems as opposed to the continuous use of mechanical ventilation systems in most commercial buildings. June/July marks the only cold months in the region, with temperature dropping to about $10^0$C during the night only. Proper building design to improve air infiltration allow proper admission of air inside the buildings naturally can solve problems of ventilation which consume lots of energy for cooling and heating purposes. Building design without regard to the impact on energy demand and environment have made use of natural ventilation in Nairobi impossible, while on the contrary the regions suits for natural ventilation. In Nairobi, the current landscape maintenance, survival and creation does not depend on natural factors, rather on high energy and technology inputs. Sustainable design principles require consideration for zoning to reduce building density to protect the environment and natural resources (Rotimi and Kiptala, 2014).

## 1.2 Indoor Air Quality in Buildings

Indoor air quality refers to the status of air inside or near a building, in terms of particulate matter, biological and chemical contaminants, pollutants, temperature, ventilation, humidity affecting the comfort of the building occupants (Wolkoff, 2018). Building ventilation systems performance affect the indoor air quality and ventilation energy requirement of the buildings (Nowak *et al*., 2018). Due to the increased concern on indoor health environment and energy use reduction, natural ventilation is one factor for consideration in designing green buildings (Nowak *et al*., 2018). Ventilation systems whether mechanical or natural remove humid and contaminated air out of the building and replace it with fresh air with less humidity and contaminants. Poor air change rate in enclosed indoor spaces contributes to increased rates of transmission of infectious diseases (Knibbs *et al*., 2011).

Additionally, ventilation systems contribute to total energy losses of a building especially in mechanically conditioned buildings where air-conditioning of outdoor air to meet required internal conditions is necessary. Trace gas method is the common method used in determining ventilation rates in buildings. Many researchers have utilized Carbon Dioxide ($CO_2$) as tracer gas as is naturally produced by building occupants (Nowak *et al*., 2018).

## 1.3 Green Building Overview

Green construction is a structured method of electing buildings that satisfy certain criteria from site selection phase to renovation of the building (Gan *et al*., 2015). It involves cradle to grave consideration of the building's energy consumption and environmental impact. Site selection for green building should consider ecological sensitivity areas; avoid areas prone to flooding, away from public green areas and cultural and commercial facilities (Kim and Shin, 2011). In site selection, the impact of the building on existing landscapes and potential change of use in the future are important considerations. Construction process should utilizing locally available raw materials, recycle and re-use of raw materials. Materials with low embodied energy and less global warming impact are the priority. Indoor environment of green buildings should be a priority and should enhance day lighting, thermal comfort and acoustic conditions of the building while controlling humidity, volatile organic content (VOC) of the materials to the minimum (Kim and Shin, 2011).

Green buildings are primarily designed for energy saving and conservation. Green buildings should minimize as much as possible energy used in operation of the building's lighting, cooling, and running appliances, water heating and air handling. Furthermore, green buildings should actively utilize renewable resources to power the buildings. Incorporating heat pumps, passive heating and cooling of the buildings, solar water heating and photovoltaic technologies to supplement utility power, while eliminating use of fossil fuels in the buildings is necessary. Green buildings should adopt energy management principles in their operations to improve on the energy efficiency in the buildings. To achieve sustainability, automation of lighting systems and equipping the buildings with occupant sensors and appliance control system to ensure energy used only when needed (Chel and Kaushik, 2018). Green buildings should utilize and store water resources efficiently. Rainwater harvesting and treatment of gray water should be a priority while designing green building to ensure that it does not completely rely on municipal water supplies and reduce operational costs (Wara, 2016).

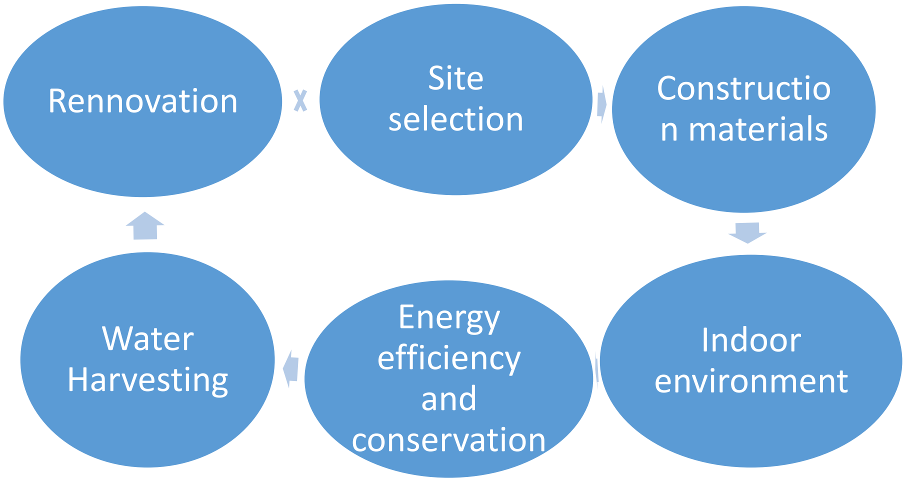


**Figure 0.1: Considerations for green buildings**

### 1.4 Metabolic $CO_2$ in Buildings and Air Quality

Temperature levels, relative humidity and pollutant concentration affect indoor air quality. According to Persily and de Jonge (2017), increased levels of metabolic $CO_2$ in buildings has been linked to increase in other indoor contaminants affecting performance and health status of occupants. $CO_2$ concentration levels in a building vary depending on physical activity and number of occupants, ventilation rate and rate off gassing from equipment and materials in the buildings (Prill, 2013). As result, these factors justify why $CO_2$ concentration are used to design ventilation systems (Prill, 2013; Laverge *et al*., 2015). Besides, increased $CO_2$ levels presents challenges on indoor air quality because, though $CO_2$ in low amounts might not affect people, it signifies possibility of increased exposure to contaminants and pollutants (Cetin, 2016; Yalcin *et al*., 2016). An adult exhales breath containing between 35,000 ppm to 50,000 ppm (Prill, 2013). Concentration levels inside a building relate directly to the number of occupants in the building, ventilation rate of the building and the concentration level of $CO_2$ in outside air (Yalcin *et al*., 2016).

## 1.5 Global and Local Energy Consumption Patterns

In United States, commercial buildings utilized more than 60% of the total energy produced. Department of Energy (DOE) projects energy use would increase by 19% by the year 2025 (Sessions, 2015). In the European countries, 40% of energy consumption is by buildings and also contribute to about 36% of greenhouse gases (Gan *et al*., 2015). EU 2020 framework aims to develop energy efficient buildings through adoption technologies to facilitate creation of smart cities in the future (Carpio *et al*., 2014). Adopting green building technology can mitigate most environmental problems associated with building pollution and improve energy efficiency (Sessions, 2015).

## 1.6 Origin of Green Buildings

Current green building initiative commenced due to energy deficiency and need to have more ecofriendly buildings. In addition, the oil crisis of 1970s encouraged more research to improve energy efficiency and adoption of renewable energy sources to supplement the conventional sources. Energy efficiency research and environmental protection campaigns yielded green building development. Although it has been long, most countries have not fully adopted green building technology while some countries are making it compulsory in their statues to adopt the technology. In Africa, concern on green buildings have been low due to lack of industrialization and most countries have not exceeded their carbon trade limits. Green building or green development is the next big technology that would fit Africa and especially Kenya due to her climatic conditions and the fact that Kenya is moving towards industrialization where more and more energy would be needed translating to more pollution and carbon emission (Ohshita *et al*., 2015; Mundaca and Markandya, 2016).

### 1.6.1 Green Building Technology in Kenya

Green Building technology has not gained much prominence in Kenya. The standards applied are those from Europe and United States for the few buildings regarded as complaint to green building principles. Several buildings in the country have been in the limelight for meeting the various criteria of green buildings. Among them are Strathmore Business School building which was constructed in compliance with Leadership in Energy and Environmental Design (LEED) system developed in United States, Catholic University Resource Center operates without any mechanical air conditioning system and UNEP building which is completely powered by solar Photovoltaic system. Understanding performance of such buildings in terms of energy use and capacity to reduce global warming would be important in policy formulation.

Recently, in the year 2018, the Government of Kenya in partnership with Green Africa Foundation (GAF), through Low Emission and Climate Resilient Development (LECRD) project under Environment and Forestry Ministry, developed the GreenMark Standard. United States Agency for International Development (USAID) through United Nations Development Program (UNDP) funded the process. The GreenMark Standard for Green Building aims to provide weighted scores for buildings constructed utilizing the green principles of energy, water, and resource and health sustainability of the buildings. The scores are awarded depending on environmental sustainability of the building starting from sustainable site selection, sustainable material and resource selection and use, sustainable energy utility, water quality and efficiency, sustainable maintenance and operation and innovation applied in the lifecycle of the building (Otieno, 2018).

## 1.7 Statement of the Problem

As Kenya becomes industrialized, energy demand has increased while the supply is unsustainable (Kimuyu *et al*., 2012; Hameed *et al*., 2014; Wiberg *et al*., 2014). Therefore, sustainable energy management technologies to tackle increasing challenges of energy demand and low energy supply are paramount. Green building is one of the energy management technologies when adopted would ensure the country is energy sufficient (Omer, 2011). Further, poor indoor conditions affect the health of occupants and their productivity as people spend more than 90% of their time indoors. However, it is imperative to conduct post-occupancy studies to validate whether the green buildings perform as designed. There is no information on green buildings' performance in Kenya and the application of GreenMark Standard to certify building is required. The purpose of the study was to determine energy and indoor quality performance of selected green buildings in Nairobi Kenya.

## 1.8 Justification

Adoption of green building by 2050 can result to 50% reduction in energy consumption and 80% reduction in greenhouse gases emission (Gan *et al*., 2015). Green building can drive vision 2030 sustainability goals and Big 4 Agenda by providing affordable housing in terms of resources utilization such as water and energy, addressing universal health by improving indoor air quality, support manufacturing by freeing energy used in buildings for industries and addressing food security by utilizing harvested rainwater for domestic irrigation. It is necessary to establish energy efficiency and indoor air quality of reported green buildings in the country before mass adoption. Testing of new technologies to validate the gains to the society and the economy of the country before its adoption is critical.

## 1.9 Objectives

### 1.9.1 Main Objective

The main objective of the study was to assess energy efficiency, indoor environment quality and sustainability testing of green buildings in Nairobi, Kenya

### 1.9.2 Specific Objectives

1. To investigate energy consumption patterns for commercial green and non-green buildings in Nairobi County, Kenya.
2. **2.** To determine adequacy of ventilation through indoor air quality assessment in green and non-green buildings.
3. **3.** To determine the sustainability of green buildings using the GreenMark Standard.

## 1.10 Research Questions

The research sought to answer the following questions:

a. Is there any difference in energy consumptions between green and non-green buildings?
b. Does the energy efficiency of green buildings justify their adoption?
c. Do the green buildings have better air change rate than non-green buildings?
d. Are the existing green buildings satisfying all energy and indoor environment conditions specified by the GreenMark Standard?

## 1.11 Scope of Study

The study focus on establishing the occupational conditions of green buildings in Nairobi, Kenya. The building used in this study are in learning institutions in Nairobi County, Kenya. Energy consumption patterns were analyzed using electricity bills in the institutions. Adequacy of ventilation determination in the study uses gas tracer method, and $CO_2$ as the tracer gas. GreenMark Standard for Green Buildings was the tool utilized to test the building sustainability.

## 1.12 Study Limitation

The study considered the total energy use of the buildings as the value indicated in the power bills from Kenya power. CO2 concentrations were used as indicators of air quality and rate of ventilations. Difficulties securing more buildings for the study meant only four buildings were used to make conclusions.

# CHAPTER TWO

# LITERATURE REVIEW

## 2.1 Theoretical Background

### 2.1.1 Energy efficiency Theories

Energy benchmarks are reference used to compare energy consumption between buildings classified in the same category. Organizations can develop internal benchmark or rely on external benchmark. Internal benchmark are institutional references for which an organization can compare its energy usage for buildings within the organization. External benchmark refer to reference by government for which energy consumption for similar buildings are undertaken. The external benchmark offer the best practice for effective energy efficient buildings (Khoshbakht *et al.*, 2018). Buildings energy utility are normalized by floor area as shown in equation 2.1

$$\eta = \frac{E}{A} \tag{2.1}$$

$\eta$= Building Energy Intensity (BEI) (kWh/m$^2$)

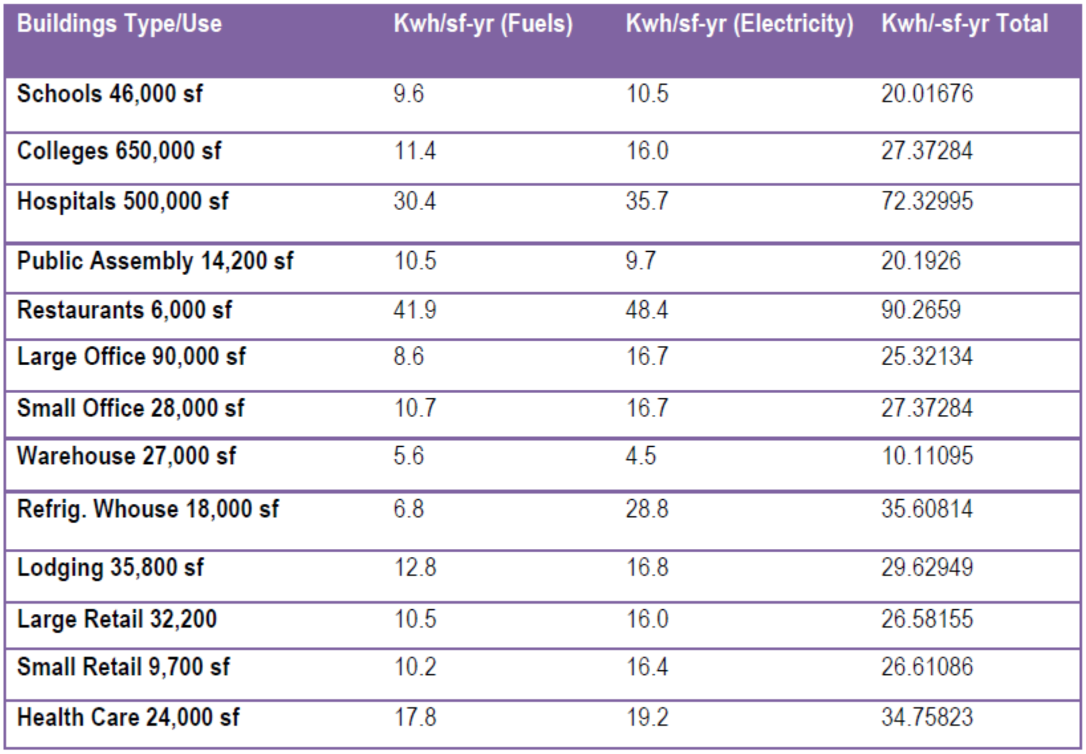
E= Total energy Consumption in kWh

A= is the total Area of the building m$^2$

Energy consumption used in calculating energy efficiencies in various ways. Energy consumption from power utility, which mainly in electronic or manual formats, provide most convenient way of estimating energy consumption. When detailed energy consumption data is required, shadow metering installed at utility service point also keep record of energy consumption. Energy from sub-meters and other automated consumption systems also utilized to obtained building energy consumptions (Khoshbakht *et al.*, 2018).

In this study energy consumption were calculated using electricity bills from Kenya Power billed to the institutions. In Kenya, energy efficiency of buildings is determined using benchmark and baseline developed by Ecocare International Ltd contracted by Energy Regulation Commission (ERC) currently named Energy and Petroleum Regulation Authority (APRA) to establish energy efficiency of the buildings (Mbogori *et al*., 2013). An extract showing maximum annual consumptions for various buildings is as shown in Table 2.1. Institutions of higher learning electricity values correspond to those for colleges.

**Table 2.1: Annual energy consumption benchmark values (Mbogori *et al.*, 2013)**



| Buildings Type/Use | Kwh/sf-yr (Fuels) | Kwh/sf-yr (Electricity) | Kwh/-sf-yr Total |
|---|---|---|---|
| **Schools 46,000 sf** | 9.6 | 10.5 | 20.01676 |
| **Colleges 650,000 sf** | 11.4 | 16.0 | 27.37284 |
| **Hospitals 500,000 sf** | 30.4 | 35.7 | 72.32995 |
| **Public Assembly 14,200 sf** | 10.5 | 9.7 | 20.1926 |
| **Restaurants 6,000 sf** | 41.9 | 48.4 | 90.2659 |
| **Large Office 90,000 sf** | 8.6 | 16.7 | 25.32134 |
| **Small Office 28,000 sf** | 10.7 | 16.7 | 27.37284 |
| **Warehouse 27,000 sf** | 5.6 | 4.5 | 10.11095 |
| **Refrig. Whouse 18,000 sf** | 6.8 | 28.8 | 35.60814 |
| **Lodging 35,800 sf** | 12.8 | 16.8 | 29.62949 |
| **Large Retail 32,200** | 10.5 | 16.0 | 26.58155 |
| **Small Retail 9,700 sf** | 10.2 | 16.4 | 26.61086 |
| **Health Care 24,000 sf** | 17.8 | 19.2 | 34.75823 |

The BEI compared with the baseline and benchmark values gives the energy efficiency of the buildings. To establish the energy efficiency of each building, the Benchmarked value divided into four quartiles. The first quartile (0%-25%) represent most energy efficient building while the 4th quartile represent the least efficient.

### 2.1.2 Tracer gas method and indoor air quality

Tracer gas techniques are widely used to measure buildings' ventilation rates, especially for naturally ventilated buildings. Generally, a tracer gas methods tag an idealized air volume to infer bulk movement of air. Considering conservation of mass principles utilizing continuity equation, one can monitor concentration of tracer gas to infer the air change rate in the building. It is difficult to establish natural ventilation or air infiltration for buildings without mechanical ventilation systems. Experimental methods such as use of tracer gas techniques become very useful (Afonso, 2013). Three major tracer gas methods exist for measuring ventilation rates in buildings: Steady-state method, decay method and build-up method (Batterman, 2017). Different equations govern the different methods shown below:

I. Steady-state method

$$A_s = 6 \times 10^4 n G_p / \{V(C_S - C_R) \qquad (2.2)$$

Where;

$A_s$= Steady-state air change rate; n=number of persons; $G_p$ Average $CO_2$ generation per person; V= volume of the space ($m^3$); $C_S$-steady-state indoor $CO_2$ concentration (ppm); $C_R$= Outdoor $CO_2$ concentration.

II. Decay method

$$A_D = \frac{1}{\Delta t} \ln\{(C_1 - C_R)(C_0 - C_R)\} \qquad (2.3)$$

Where $A_D$=Decay air change rate; Δt = period between measurements (h); $C_0$ and $C_1$ = measured $CO_2$ concentrations over the decay period (ppm); and $C_R$ = $CO_2$ concentration (ppm) in outdoor air

III. Build-up Method

$$A_B = \frac{1}{\Delta t} ln \left\{ \frac{C_S - C_0}{C_S - C_1} \right\} \qquad (2.4)$$

Where Δt = period between $C_0$ and $C_1$ measurements (h), $C_S$ = steady-state concentration (ppm), and $C_0$ and $C_1$ = $CO_2$ concentrations measured at start and end of the observation time window, respectively (ppm).

Simplifying eqn. 2.4 we get;

$$I = \frac{1}{t} . \ln(\mathrm{c}) \qquad (2.5)$$

*I* is the air change rate ($h^{-1}$)

c is the difference in indoor and outdoor $CO_2$ concentration (ppm)

t is the time of the day (hours)

The following equation give an expression for calculating ventilation rates;

$$v = I * V \qquad (2.6)$$

Where;

$I$ is the air change rate ($h^{-1}$)

ν is the ventilation rate (airflow rate) ($m^3/h$)

V is the volume of the building ($m^3$)

Gases used in tracer gas method can be metabolic products such either as $CO_2$ or artificially injected in the buildings. Due to environmental impact of artificially injected tracer gases, $CO_2$ has become more convenient tracer gas. CO2 offer cheap, fast, simple and reliable method of estimating ventilation rates in buildings (Edouard *et al*., 2016). $CO_2$ concentration provides a cheaper and easier method for air-change rate measurement. The level of $CO_2$ in buildings is proportional to impurities and contaminants in the building space that affect indoor air quality. Further, use of metabolic $CO_2$ as tracer gas eliminates introduction of other gases such as sulphur hexafluoride ($SF_6$) in the building space, which has higher greenhouse effects. $CO_2$ provides the stable and inert characteristics needed for tracer gases (Beko *et al*., 2016; Batterman, 2017). Preferred tracer gases should be inert, non-toxic in ambient conditions and measurable and $CO_2$ satisfies all the conditions of tracer gases (Afonso, 2013; Nowak *et al*., 2018).

Temperature and humidity affect indoor air quality. Virus and bacteria thrive in extremely high humid environments, as does mold spores and other allergens and off-gassing activities. Ensuring acceptable humidity levels in buildings is key to achieving high quality indoor air. Acceptable humidity levels range between 40% and 60%. Higher temperatures indoor air quality, recommended temperature levels inside buildings range from 20 ℃ to 25.5 ℃ (Laue, 2018). Increased levels of metabolic $CO_2$ in buildings indicates increase in other indoor contaminants affecting performance and health status of occupants. Besides, increased $CO_2$ levels presents challenges on indoor air quality because, though $CO_2$ in low amounts might not affect people, it signifies possibility of increased exposure to contaminants and pollutants (Celtin, 2016; Yalcin *et al*., 2016).

### 2.1.3 Building sustainability testing

World Green Building Council (WGBC), an affiliate of more than 80 building councils in different countries, fast tracks transformation of conventional buildings into green buildings. The council has a goal of sustainable construction to reduce effects of climate change and $CO_2$ emissions. WGBC further works to help adoption of market-based green building rating and criteria systems that are country specific. Most of the countries adopt the ratings depending on the priorities set by the country because there is no universal rating system (Bahaudin *et al*., 2014). Having energy efficient buildings is critical to environmental degradation, mitigation and conservation of natural resources. United States leads the process of policy formulation regarding green building with several rating systems adopted to classify the level of green technology in each specific building.

Different rating standards have specific elements and categories that buildings should satisfy to be rated as green or sustainable. Checklists that officers use to analyze buildings components and performance with regard to specific categories inform scores awarded to each particular building. The GreenMark Standard established the checklist for each category as shown in Appendix 28, 29 and 30.

## 2.2 Related Literature

### 2.2.1 Green Building

Environmental Protection Agency defines a green building or sustainable building or high-performing building as structures that are environmentally responsible and resource-efficient throughout a building's life cycle from siting to design, construction, operation, maintenance, and renovation phases. This practice expands and complements the classical building design concerns of economy, utility, durability and comfort. Federal Environmental Executive office defines a green building as the practice of first, increasing the efficiency with which buildings and their sites use energy, water and materials and second, reducing building impacts on human health and the environment, through better siting, design, construction, operation, maintenance, and removal during the entire building life cycle. The definition of a green building factors life cycle assessment of the building in regards to the economy, health, environment and social impacts. It does not factor the immediate condition of the building rather it takes the impact throughout the life of the building (Howe, 2010).

### 2.2.2 Status of Green Building

Building sector is an important sector for any economy to grow. However, buildings consume a lot of energy, water and raw material, while being a major environmental polluter (Shaikh *et al*., 2014). The major focus of green building is to reduce energy consumption of the building sector. In addition, occupant comfort and health are also priorities that green buildings aim to achieve. Global warming is an environmental degradation aspect that all sectors of the economy are focusing to address and green building sector can help address the issues of global warming (Ohshita *et al*., 2015). In essence, energy conservation results to reduced production of carbon dioxide, a greenhouse gas, due to reduced reliance on fossil fuels to produce power needed in the buildings. Green building concept has the potential to bolster green development (Omer, 2011). Certain objectives are important in developing green buildings: energy and resource efficiency; pollution prevention; GHGs emission reduction; noise mitigation; indoor air quality improvement and environmental friendly (Pueyo *et al*., 2015). The cost of putting up a green building should be low while ensuring that minimal maintenance is required and should return to earth in its entirety when abandoned (Akadiri *et al*., 2012).

Global status will shift greatly by 2056 if left undisturbed; fivefold increase of global economy, about 50% increase in population, about threefold increased energy consumption and manufacturing possibly increasing threefold projected. For instance, fossil fuels are common in construction industry and have had fears due to the impact it could have on energy resources depletion and environmental impacts such as $CO_2$

emission, ozone layer destruction, climate change and global warming. All stages of building construction consume enormous amounts of energy: construction stage, material production stage, running a completed building require energy. In addition, 40% of global environmental pollution results from buildings (Akadiri *et al*., 2012).

### 2.2.3 Considerations in Designing Green Buildings

Initial cost, which is marginally higher than the cost of developing conventional buildings, hinder implementation green building projects. Green buildings require systems developed with new technology in order to enhance utility and comfort of the buildings. Several differences exist between conventional buildings and green buildings. The differences are generally design related. Conventional buildings reflect light while green buildings absorb light. Conventional buildings insulate solar energy, green buildings use and absorb solar energy. Conventional buildings shed rainwater while green buildings use and capture rainwater. Lastly, conventional building produce high wastewater while green buildings treat, store and re-use any wastewater (Chel and Kaushik, 2018).

A green building should be as natural as possible to help mimic outdoor conditions in the indoor space. Solar resources are critical in green buildings in aiming at reducing energy consumptions in the buildings. Green buildings utilize daylight illumination to eliminate use of electricity for lighting purposes during the day. The buildings have various features to help enhance daylight illumination (Da Silva *et al*., 2018). The buildings should be fitted with glass roofing or coating to allow light into the building during the day. In addition, shading devices and auto dimmers regulate the light entering the buildings at each particular time. Motion sensors are also important in the buildings to help switch on and off the lights depending on utility status the building space. Reflective surfaces such as light shelves regulate the level of illumination in the buildings (Wang *et al*., 2018).

Solar heating measures incorporated in the buildings reduce energy usage in heating water for domestic purposes. Roofs, walls, floors and windows can be fitted with heat storing, collecting, distributing and releasing systems to help reduce the cost of maintaining suitable conditions in the buildings (Lee, 2013). Solar passive techniques help in provision of day lighting, cooling and heating requirements of any building. Proper combination of the features involves solar energy collection through windows that are oriented on the north-south direction. (Green buildings should be oriented in the North- South directions particularly to allow proper penetration of light and avoid uneven heating of the building as time of the day changes). The energy is stored in the building as thermal mass by use of high heat capacity building materials like brick walls, tile floors and concrete slab. Radiation and natural convection mechanisms redistribute energy stored in the building space. To enhance passive solar heating mechanism in green buildings, all the components must work together (Chel and Kaushik, 2018).

The components of solar passive heating include; aperture, which is a large window (glass) inclined $30^0$ of the true south. The aperture should be away from shading caused by tall buildings and trees mostly throughout the day. An absorber, which should be hard and darkened to enhance its ability to absorb heat from the sun. The absorber could include partitions fitted with phase changing materials, floors or masonry walls. Thermal mass, which comprise the material responsible for retaining or storing absorbed heat from the sunlight. Thermal mass is the material behind or below the absorber. The distribution method of the absorbed and stored heat. Since it is a passive system, it should utilize natural heat transfer methods, rather than forced heat transfer methods, which include convection, radiation and conduction (Chel and Kaushik, 2018).

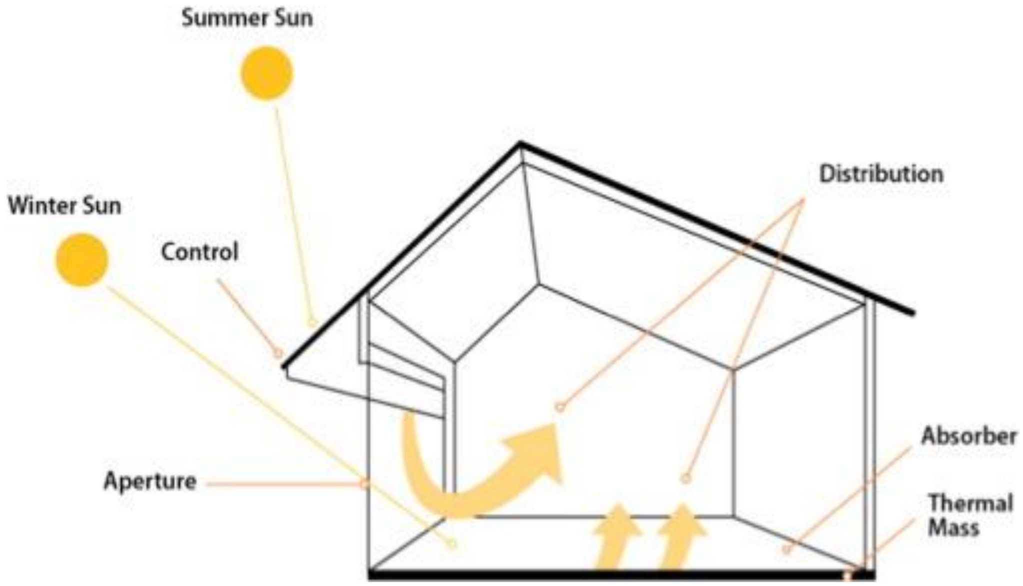


**Figure 0.1: Solar Passive Heating Component; source: Chel and Kaushik, 2018.**

Energy performance of buildings fitted with phase changing material that have thermal storage capacity reduce dependence on fossils in buildings (Soares *et al*., 2013). Use of phase changing materials (PCM) can reduce the energy needed to cool and heat a building. Fitted PCM on walls, floors, windows, ceilings, and the phase change passively without use of mechanical devices. The systems can greatly help reduce energy demand and environmental pollution. PCM change from solid to liquids when the temperatures increase in an endothermic process in which heat is absorbed (Soares *et al*., 2013). When the temperatures decrease, the phase change from liquid to solid happens in an exothermic process releasing heat into the building. Instead of fitting houses with heating, ventilation and air conditioning systems (HVACs) that consumes energy, buildings can be fitted with PCM that regulate the building temperatures through change of phase while releasing or absorbing heat (Soares *et al*., 2013).

Solar passive heating in green buildings in diverse ways; directly heating the building space, functioning as heat collection, absorption and distribution medium. The thermal mass (walls and floors) absorb and store solar energy during the day and radiate to space during the night. Indirectly, water walls and Trombe walls store heat energy during the day and release the energy during the night (Chel and Kaushik, 2018). Isolated gain solar energy move heat to and from a building space through fluids like water and air. Further, plate collectors generate heating and cooling effect on building (Basecq *et al*., 2013).

Green buildings with control mechanisms reduce possibility of overheating and under heating of the building space. Such control mechanisms include electronic sensors such as thermostats to regulate fans; roof overhangs utilized during summer for shading. Operable dampers and vents to restrict and allow heat flow, awnings and low-emissivity blinds. The major use of the control system in the passive system is to reduce loss of the absorbed heat. The aperture fitted with mechanical or automatic control systems regulate the amount of absorbed and distributed solar heat. They could be both operable and non-operable window coverings to regulate sunlight entering the building. In addition, cellular shades on the aperture reduce heat loss during the seasons the building require heating and prevent unwanted solar heat during seasons the buildings require cooling. Window quilts like the cellular shades allow or limit solar heat in the building. Roller shades, curtains, drapes, blinds and window films are other interior mechanisms used passively regulate solar heating in a building. Exterior mechanisms for solar heating control include exterior shades and shutters, awnings and solar screens fitted on the windows all aimed at regulating the amount of heat received by the building (Basecq *et al*., 2013).

Fitting green buildings with solar photovoltaic (PV) system minimize the cost of powering the buildings from grid power. The PV systems convert solar energy into electricity supplied in the buildings for utility. The use of PV system is important because it minimizes GHGs emissions. Green buildings entirely depend on renewable energy from PV system or have hybrid system that incorporates PV system with national grid system. Buildings that entirely rely on onsite power supply from renewables are Net Zero Energy Buildings. The idea behind NZEB is to solve energy saving problems, reduction of $CO_2$

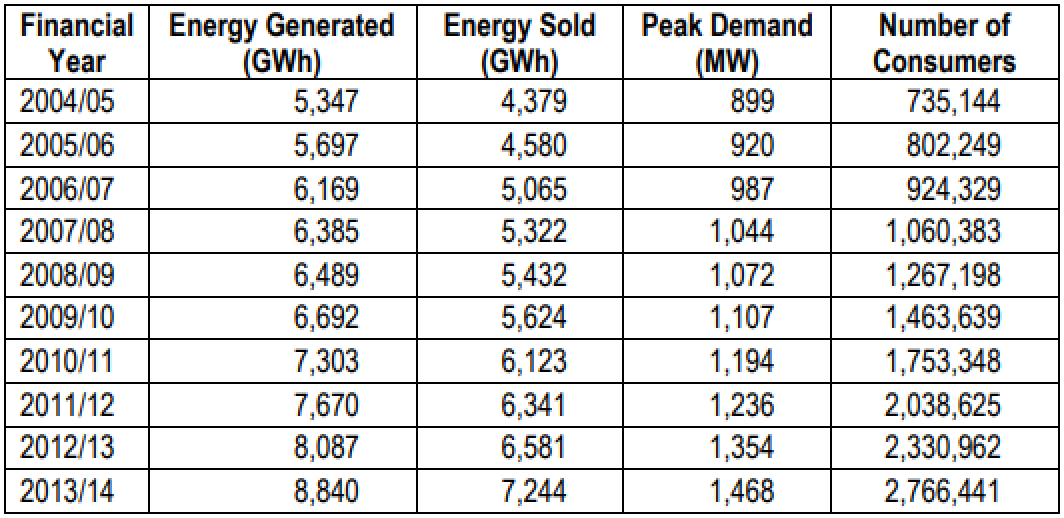
emissions and provide environmental protection. Adoption of renewable energy in buildings is the most viable solution to energy security, global warming and air pollution. Energy storage in buildings, thermal or electrical, addresses peak and off-peak instabilities. Due to climatic conditions that affect supply of renewables, supplementing with grid power is important. When the renewable system produces extra power, it is sold to the grid, when the system produces low power, the system is supplied by the grid power to ensure sustainability and productivity throughout. To reduce cost of operation of PV system in green buildings, investors adopt Power Purchase Agreements (PPA). PPAs allow the building to avoid the cost of installing storage system as the excess power produced during the day is fed to the main grid and compensated during the night when solar energy is lacking (Deng *et al*., 2011).

### 2.2.4 Energy Demand, Energy efficiency and SBT in Kenya

Energy remains the major resource to transform a developing country into a developed one thus critical for any country's economy, health and population's wellbeing (Wekesa *et al*., 2016). Kenya, for instance, experiences an energy and environmental crisis due to the sustained reliance on woody biomass (68%), Petroleum fuels (22%), and electricity (9%) (Eshiamwata *et al*., 2019). These competing energy sources negatively affect the environment. In addition, electricity mainly hydropower produced is highly unreliable due to persistent droughts with consequential drying of water reservoirs. Despite the country's struggle to solve energy challenges, like establishing plants driven by geothermal and diesel generators, energy cost continued to rise in the last decade (Wekesa *et al*., 2016). In the recent years, plenty of research on integrating solar and biomass energy system are under the spot light as it helps in self-sufficient and green rural electrification and also boosts the native community to utilize the bio-waste comprehensively (Reddy *et al*., 2016).

Energy demand in Kenya has been increasing each year due to ambitious plans of the government to have the country industrialized by 2030 (Kinoti, 2017). Table 2.1 shows energy demand between 2003 and 2014. For instance, Kinoti (2017) projected the demand to be 5359MW in 2018 up from 1512MW in 2014 due to economic and population growth in the country. The Standard Gauge Railway, LAPPSET, industrial parks, resort cities and the 4 economic development Pillars “BIG FOUR” of the government are supposed to shift energy demand to the upper side. The country has been relying on power Imports from Uganda and Ethiopia to supplement deficiencies experienced especially due to droughts affecting hydropower production. Power demand has pushed adoption of Independent Power Producers (IPPs) some of whom have installed fuel oil plants contributing to environmental pollution (Kenya Power, 2016). The Kenya Energy Policy (2015) recognizes that energy saving and conservation in Kenya has not been exploited majorly due to lack of awareness of the benefits of energy saving and lack of knowledge of methods of energy conservation, limited data and lack of technical capability. The responsibility of creating awareness belongs to the government, in addition to developing strategies and undertaking research to inform on energy efficiency and conservation.

**Table 0.2: Annual energy consumption patterns: MoE (2015)**



| Financial Year | Energy Generated (GWh) | Energy Sold (GWh) | Peak Demand (MW) | Number of Consumers |
|---|---|---|---|---|
| 2004/05 | 5,347 | 4,379 | 899 | 735,144 |
| 2005/06 | 5,697 | 4,580 | 920 | 802,249 |
| 2006/07 | 6,169 | 5,065 | 987 | 924,329 |
| 2007/08 | 6,385 | 5,322 | 1,044 | 1,060,383 |
| 2008/09 | 6,489 | 5,432 | 1,072 | 1,267,198 |
| 2009/10 | 6,692 | 5,624 | 1,107 | 1,463,639 |
| 2010/11 | 7,303 | 6,123 | 1,194 | 1,753,348 |
| 2011/12 | 7,670 | 6,341 | 1,236 | 2,038,625 |
| 2012/13 | 8,087 | 6,581 | 1,354 | 2,330,962 |
| 2013/14 | 8,840 | 7,244 | 1,468 | 2,766,441 |

According to Howe (2010), the most important aspect of a green building is energy efficiency. If a building does not utilize the energy efficiently, then it would be difficult to consider such a building as sustainable or high performing or green building. Research shows that buildings consume more than 40% of the total energy produced globally while they are responsible for about 30% of total carbon dioxide emissions globally (Allouhi, *et al*., 2015). Buildings, in United States, are projected to increase energy consumption by 19% by 2025 (Wang *et al*., 2018). Energy efficiency also concerns the input output ratio of the energy applied. Most countries utilize their energy inefficiently such that it is economically inefficient to use energy. To prevent escalating energy demand, green building is the next option. Policies and regulation should be put in place to ensure that Kenya does not move towards the energy crisis way. According to European commission, 2011, buildings contributed to 16% of total emissions. European countries established a compulsory time-of-transfer performance certification as form of compliance to energy performance policy for buildings. Since 2008, all member states should comply with Energy Performance of Building Directive (EPBD) (Sessions, 2015). In Australia, home owners should disclose building energy use (Hsu, 2014; Sessions, 2015). Buildings' energy consumption in United States increased from 33% in 1980 to 41% in 2012 (Begum *et al*., 2015). Cancun and Copenhagen Treaties require that all developed states to reduce their emissions and maintain the global warming at 2 $^0$C (Wara, 2014; Lee, 2015). The European Union projects GHGs emission reduction by a range of about 90% by 2050 through adopting measures to increase energy efficiency (Allwood *et al*., 2010).

### 2.2.5 CO2 Measurement Importance and Technology

#### 2.2.5.1 Importance of $CO_2$ Measurement

Metabolic $CO_2$ concentrations in a building determine building ventilation adequacy. Contaminant concentration and rate of air change in buildings affect air quality inside a building. Outdoor air remove and dilute contaminants and other pollutants inside the building. Metabolic $CO_2$ is expressed in parts per million (ppm), the amount $CO_2$ molecules present in a million molecules of air. $CO_2$ concentration provides a cheaper and easier method for ventilation measurement as it relates to impurities and contaminants that affect indoor air quality in building space. $CO_2$ concentration build-up in buildings show inadequate ventilation needed to remove and dilute $CO_2$ inside the building from the building occupants. Air outside and inside a building mix through ventilation system which could either be natural or mechanical (Prill, 2013).

#### 2.2.5.2 $CO_2$ Measurement Technology

$CO_2$ meters used to measure $CO_2$ concentrations are inexpensive and easy to use. Ventilation rates calculation using the tracer gas method involve measurement of both indoor and outdoor $CO_2$ concentration (Nowak *et al*., 2018). Typical outdoor $CO_2$ concentration levels range between 380 ppm to 500 ppm. $CO_2$ meters present in market can measure $CO_2$ only, others can measure $CO_2$, humidity and temperature and others gases like Carbon monoxide (Prill, 2013). Some advanced meters measure volatile organic compound (VOC) used to infer levels of $CO_2$ concentrations in the building. Indoor concentration in buildings should not exceed the outdoor concentration by a value more than 650 ppm (McNulty *et al*., 2019). In addition, as the $CO_2$ concentration increases, other indoor contaminants also increase hence exposing occupants to distracting, irritating and possibly unhealthy particulates and gases (Prill, 2013).

### 2.2.5.3 Using $CO_2$ to Measure Ventilation Rate

Ventilation rate study utilizing tracer gas methods require the zone or the building to achieve steady-state equilibrium with the surrounding to minimize errors. For buildings that have low ventilation rate, the levels of $CO_2$ could increase without reaching equilibrium throughout the day. On the other hand, good mixing and high ventilation rate minimize $CO_2$ accumulation beyond recommended levels (Prill, 2013). Allowing the building to reach equilibrium is necessary before measuring concentration levels so that the reading would reflect the accurate ventilation rate of the building. Some errors though in establishing ventilation rate through $CO_2$ measurements could arise due to: significant fluctuating occupancy rates, calibration problems of the equipment, having ventilation system that modulate the amount of outside air allowable during the day, measurement location or poor mixing of air in the space (Labeodan *et al*., 2015). $CO_2$ sensors monitor concentration levels in a building, which the HVAC system utilize in modulating the volume of outdoor air required. Demand-controlled ventilation in buildings save energy as only the required outdoor air is conditioned (Prill, 2013; Labeodan *et al*., 2015).

Ventilation rate is important in determination of building air quality and energy consumption. Building ventilation with outside air is required to maintain indoor environmental conditions at suitable levels to avoid discomfort, health issues, productivity and absenteeism in work places (Batterman, 2017). Ventilation systems whether mechanical or natural allow fresh air inside the building replacing humid and contaminated air out of the building necessary for internal air quality control. Whether it concerns energy saving or air quality in the building, establishing adequacy of ventilation or efficiency is necessary (Nowak *et al*., 2018). Air change rate in naturally ventilated buildings depend on geographical location, whether conditions, building characteristics and occupant behaviors (Beko *et al*., 2016). Building design and orientation are important determinants of air change rate, as they dictate air movement between the indoor and outdoor environments of the buildings (Chel and Kaushik, 2018). In most buildings, heating, ventilation and air conditioning (HVAC) systems consumes considerable amount of energy. In United States, HVAC systems account for 50% of energy consumed in buildings while constituting 20% of the total energy consumed in United States (Batterman, 2017).

Increased concern on indoor health environment and energy use reduction highlights natural ventilation as one factor for consideration in designing green buildings (Nowak *et al*., 2018). $CO_{2}$, as tracer gas, produced by building occupants hence cheaper testing without requirement of mechanical emitters (Beko *et al*., 2016; Batterman, 2017; Nowak *et al*., 2018). Most studies have considered buildings as single zone and use single air change mean as the measurement for the entire building (Beko *et al*., 2016). However, considering inter-zonal air changes within the building envelop eliminates errors occasioned by assuming a single zone analysis (Afonso, 2013; Gough *et al*., 2013; Nowak *et al*., 2018).

Experimentally, adequacy of ventilation and air change (Mechanical, natural or infiltration) can be calculated using the tracer gas method and applying the mixed mass balance model (Afonso, 2013; Batterman, 2017; Nowak *et al*., 2018). The method utilize either metabolically generated $CO_2$ or $CO_2$ introduced mechanically. The evolution of the tracer gas concentration with time analyzed mathematically to determine the flow rates in the building envelop. However, the building envelop is considered a single zone in the analysis method. Three major methods use the tracer gas methods: the decay method, constant concentration and constant tracer emission. The decay method used mostly due to its simplicity (Afonso, 2016). Tracer gases must satisfy certain conditions which include being inert, odorless and with minimal impact to the environment. Use of $CO_2$ in ventilation rate determination is suitable because it is inexpensive as the gas readily available in the air, can be easily generated and the equipment are easy to read and affordable. Metabolically generated $CO_2$ makes the measurement more cost effective because no $CO_2$ emitters are needed (Nowak *et al*., 2018).

Batterman (2017) used the $CO_2$ concentration method to establish ventilation rates in classrooms, similar to Mahyuddin *et al*., (2013) who considered spatial distribution of $CO_2$ in the buildings. Nowak and others (2018) used metabolically generated $CO_2$ to determine ventilation rate in an office room. $CO_2$ in buildings is generally from bio-effluents and human activities in the buildings. Due to ventilation, the indoor air is constantly mixing with the outdoor air, which also introduce $CO_2$ in the indoor environment from environmental polluters like vehicles and industrial activities. Beko *et al* (2016), analyzed air change rate and inter-zonal airflows using occupant-generated $CO_2$ as a passive tracer gas in homes. Consideration of spatial distribution and variation in $CO_2$ concentration in the building envelop eradicate use of building envelop as a single zone.

Natural ventilation plays an important role in energy conservation, carbon emission reduction, and indoor air quality and comfort improvement. In regions with favorable climatic conditions (humid and hot), natural ventilation can eliminate and/or reduce usage of air conditioning systems (Guo *et al*., 2015). For effective natural ventilation, building design and shape should factor thermal and wind pressure ventilation systems (Guo *et al*., 2015). Building design should consider seasonal variations and the impact they have on building comfort, energy use and indoor environmental quality. Regions that do not experience extreme weather conditions can entirely rely on natural ventilation while hybrids ventilation system (mechanical and natural ventilation) are suitable for those regions that experience extreme seasonal variation. Buildings with wind chimneys utilize cross-ventilation, while others designs creates stack ventilation or water evaporation system during hot seasons to facilitate air movement in the buildings (Akadiri *et al*., 2012).

### 2.2.6 Economic Benefits of Green Buildings

Polesello and Johnson (2016) found that adopting energy efficient buildings would contributed to lowering cost of maintaining global warming below the recommended level of $2^0$C by $2.8 trillion by 2030. Failure to implement policy on energy consumption in buildings will result to increased GHGs emissions. Adopting green building technology minimizes Energy consumption and $CO_2$ emissions from the buildings. Retrofitting existing buildings reduce its GHGs emission and energy use.

Hyland *et al*., (2013) investigated the effects of green building rating on the capability of renting and selling of properties. According to them people in Switzerland were willing to pay more for energy efficient buildings. Individuals could pay 8% more for house with better ventilation and about 7% more for insulated houses. House prices increased proportionally for every increased score on energy efficiency (Hyland *et al*., 2013). In China, houses marketed as green received better buying prices. However, later the buildings sold at discounted prices because the buildings performed below expectation as the country lacked proper green rating system. In German, every single percentage increase in energy efficiency attracted about 0.08 % value of buildings (Lopez *et al*., 2018). The years 2008 and 2009, 31000 homes sold in Netherlands with rating of A, B and C had 3.7% premium price in comparison with other buildings (Sessions, 2015). In Portland Oregon, homes with Earth Advantage rating sold for 3%-5% higher than those without and 18 days faster, while in Seattle, homes with the Earth Advantage rating sold for 9.6% more than buildings without the rating (Stuart, 2011).

### 2.2.7 Green Buildings’ Energy Efficiency

Nguyen and Aiello (2013) stated that green buildings should utilize less energy as designed. The building technologies, products and design should utilize less energy from other sources, especially, conventional sources and utilize less energy compared to normal buildings. In addition, the authors indicate that such green buildings should reduce energy consumption through use of equipment and materials that are highly energy efficient, produce local energy from waste resources and renewables and apply smart generating grids. Utilization of passive design methodologies in construction of buildings can reduce energy demand in a building (Hameed *et al*., 2014; Nguyen and Aiello, 2013).

Different studies concerning energy utilization in commercial houses have been developed and technologies such as sensory devices that identify presence of individuals within the building and provision of control apparatus to ensure the building provides optimum living conditions (Labeodan *et al*., 2015). Placing sensors in a building helps regulate the indoor conditions of the building. The European Union has funded many projects to evaluate and install systems that consider humans and their comfort in the building. Other systems forecast the conditions in the building and guide in design of the buildings to accomplish green construction (Nguyen and Aiello, 2013). Usually system design does not guarantee complete performance, but the actual building performance might vary from the predicted performance level due to climatic and occupational conditions. Some buildings might have very low energy usage because they lack proper lighting, heating and ventilation but might not serve the people occupying the building effectively. A building, in essence, should provide good conditions for those occupying the house. Energy utilization per unit area of the floor or energy intensity is the most common determinant of energy performance. Countries create or establish certain threshold to gauge the energy efficiency of a building through a standard or code. Energy consumption in buildings is influenced by various factors, however, wasteful behaviors majorly due to lack of understanding of energy conservation contribute to more than double energy that could be saved as shown in the Fig. 2.2 (Nguyen and Aiello, 2013).

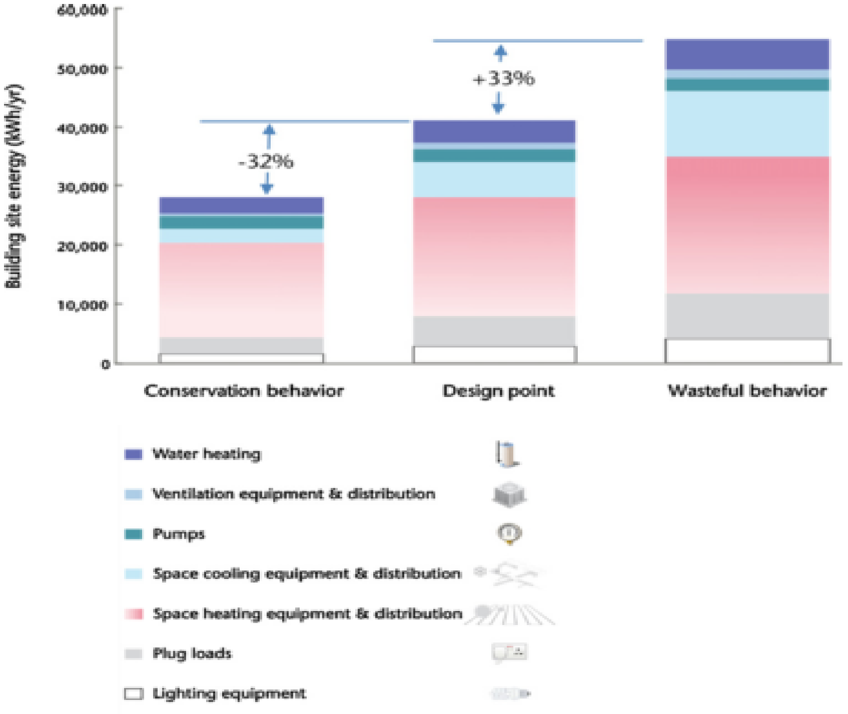


**Figure 0.2: Energy use Behavior; source (Nguyen and Aiello 2013)**

The predicted energy consumption in many green buildings do not match the actual energy consumption in the buildings (Hsu, 2014). Most buildings perform below the simulated performance level necessitating the energy consumption analysis of the buildings to compare the predicted and actual energy consumption. Performance disclosure for buildings is necessary for decision making on policy and enforcement (Hsu, 2014). Some researchers have found that some retrofitted and newly constructed green buildings use more energy than the original conventional buildings. Reduced energy consumption is a very critical aspect of green buildings, therefore the objective of achieving a low energy consumption is very important (Hamdy *et al*., 2016). Some studies have shown deviation of about 25% to about 75% from the predicted energy consumption before after the occupation of the buildings based on simulated models of the buildings (Kneifel and Webb, 2016). Most green buildings comprise state of art complex and efficient equipment hindering operation at optimal energy efficient conditions. Although such equipment might possess the best properties from a design perspective, operational parameters might differ completely (Hsu, 2014; Kneifer and Webb, 2016).

### 2.2.8 Green Building Standards

#### 2.2.8.1 LEED Certification

Leadership in Energy and Environmental Design (LEED) is an internationally acknowledged certification system for green buildings. LEED allow for third-party authentication that design and construction of a building utilized strategies stipulated for improving performance in relation to; water efficiency, energy efficiency, improved indoor conditions, reduction of $CO_2$ emissions, impact sensitivity and proper use of resources. Developed by United States Green Building Council, LEED provides building operators and owners with a framework for implementing and identifying measurable and practical green building operations, designs, and maintenance and construction solutions. LEED rate residential and commercial buildings throughout the lifecycle: design, operation, *construction*, tenant fit-out, retrofit and maintenance. In addition to LEED, different States in United States have national certification systems (Bahaudin *et al*., 2014). It is important to note that building certification is not mandatory. LEED certified buildings attract incentives like zoning allowances and tax rebate.

**Table 0.3: LEED scoring criteria for green buildings (source Bahaudin *et al*., 2014).**

| Criteria | Scoring |
|---|---|
| Energy and Atmosphere | 17 |
| Water Efficiency | 5 |
| Sustainable Sites and Transportation | 14 |
| Indoor Environment Quality | 15 |
| Material and Resources | 13 |
| Innovation & Design Process | 5 |
| Total | 69 |

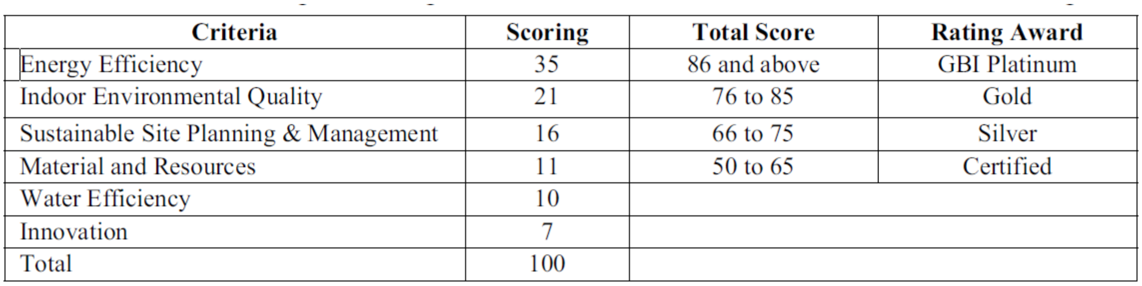
#### 2.2.8.2 Energy Performance of Buildings Directive (EPBD)

The European Union has established compulsory certification of all buildings for member states. The primary purpose of the energy framework is to save and conserve the final energy and related parameters like energy costs, $CO_2$ emissions and primary energy without compromising productivity and comfort. Green buildings rating in EU offer independent standards of assessment for building sustainability and performance. However, each region or country has its own rating system varying from country to country (Carpio *et al*., 2014).

#### 2.2.8.3 Building and Construction Authority (BCA) Green Mark Scheme

BCA Green Mark Scheme is an initiative in Singapore aimed at propelling construction industry towards environmental-friendly buildings. The aim of the initiative is to create more awareness in built environment sustainability among different stakeholders in the construction sector. BCA Green Mark intents to facilitate energy, material resource and water use reduction, minimize possible environmental impact and improve indoor environmental quality. The Green Mark score consists of all numerical points awarded in each category of the set values. Energy efficiency, water efficiency, sustainable maintenance and operation, Indoor Environmental Quality and Green innovation are the major categories for scoring. Table 2.3 shows scoring and credits for Green Mark Scheme.

**Table 0.4: Singapore's BCA Green Mark Scheme (Bahaudin *et al.*, 2014).**



| Criteria | Scoring | Total Score | Rating Award |
|---|---|---|---|
| Energy Efficiency | 35 | 86 and above | GBI Platinum |
| Indoor Environmental Quality | 21 | 76 to 85 | Gold |
| Sustainable Site Planning & Management | 16 | 66 to 75 | Silver |
| Material and Resources | 11 | 50 to 65 | Certified |
| Water Efficiency | 10 | | |
| Innovation | 7 | | |
| Total | 100 | | |

The GreenMark Standard for Green Buildings

The GreenMark is Kenya’s green building rating system created in the year 2018 to assist in development of green buildings in the country, customized to fit the conditions of the country. The GreenMark standard awards points that result to the final score based on broad categorization of environmental impact the building has including: energy efficiency, Indoor Environmental Quality, water conservation and efficiency, operation maintenance and management, innovation and Materials and resources. Cumulative weighting for the above characteristics of the buildings produce a single score (Otieno, 2018). The buildings are rated platinum, diamond, gold, silver or bronze depending on the cumulative weighting score as shown in Table 2.4

**Table 0.5: Kenya's GreenMark Standard criteria and scoring system (Otieno, 2018)**

| Criteria | Scoring | Total Score | Rating Award |
|---|---|---|---|
| Sustainable Site planning and development | 15 | 91-100 | Diamond |
| Sustainable Materials and Appropriate Technology | 10 | 85-90 | Platinum |
| Renewable Energy and Energy Efficiency | 20 | 75-84 | Gold |
| Water Efficiency and Quality | 20 | 65-74 | Silver |
| Health Indoor Environment | 20 | 50-64 | Bronze |
| Operation maintenance and decommissioning | 10 | | |
| Innovation | 5 | | |

# CHAPTER THREE

# MATERIALS AND METHODS

## 3.1 Study Area and Population

Four buildings considered in this research are at Strathmore University ($1.3089^0$ S, $36.8121^0$ E) and Catholic University of Eastern Africa (CUEA) ($1.3522^0$ S, $36.7568^0$ E); two buildings in each institution. The buildings coded as GB1 and NGB1 at Strathmore University and GB2, and NGB2 at CUEA. GB1 occupies on an area of 2050 $m^2$ for the basement, 1670 $m^2$ on each of three floors. GB1 relies on renewable energies (Solar powered) during the day with installed capacity of 600kW, while excess power produced during the day sold to KPLC through the Power Purchase Agreement (PPA) (Da Silva and Ssekulima, 2015). During the night, the building power supplied to the building by KP compensated by excess power sold during the day. GB1 has glass roofing and wall curtains that allow for day lighting, two waterfalls for cooling the building, evaporative cooling system to maintain ambient conditions. GB1 also is oriented in the North-South direction to reduce direct solar radiation and windows are set into the wall to increase shading, in addition, to roof overhangs. GB1 uses energy efficient electronic ballast lighting system for efficient energy use. Further, rainwater is harvested, stored in underground tanks and used and re-use in the building. The harvested water caters for 90% of water needs in the building (Da Silva and Ssekulima, 2015). NGB1 is conventional two-floor building adjacent to GB1. Powered by national utility grid (Kenya Power), and oriented in the East- West direction, occupies an area of 932.8 $m^2$, each floor.

GB2 library section occupies 2214 $m^2$ is powered by the Kenya Power. It is oriented in the North-South façade to facilitate natural day lighting without direct solar heating of the building. GB2 was constructed utilizing locally available materials; Mazeras paving, Njiru stones, Mvule timber and Rongai stones. GB2 has enhanced Natural air ventilation through windows and ventilation cowls and ventilation louvers across the walls.

Rainwater harvesting into an underground tank and used for tree and lawn watering (Kimani and Kiaritha, 2019). NGB2, on the other hand, is conventional three floor office block in the institution and occupies an area of 1319 m$^2$ across the three floors and GB1, NGB1 and NGB2 have height of 2.8 meters each floor while GB2 has floor height of 4.0 m.

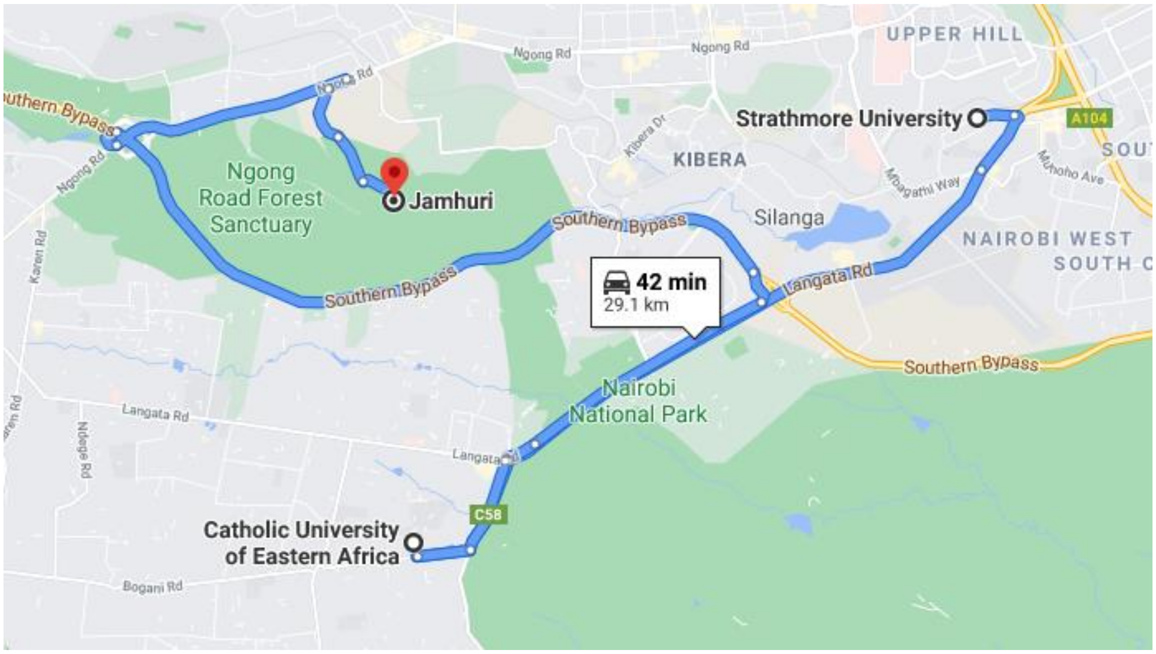


Figure 0.1: Study area (Google Maps, 2020)

## 3.2 Research Design

The study covers three broad areas namely:

a. Energy consumption and energy efficiency evaluation
b. Air change rate, ventilation rate, indoor air parameters
c. Sustainability testing of the buildings

### 3.2.1 Energy Consumption and Energy Efficiency Evaluation

Energy consumption patterns calculation utilized the energy bills supplied by the Kenya Power (KP) for each specific building from January to December 2018. As indicated in section 2.1.1, use of power bills from utility providers provide a long-term analysis of energy consumption patterns in a building. Monthly energy bills were added together from January 2018 to December 2018 to get the total annual energy consumption for the whole year. As indicated in equation 2.1, to calculate BEI, the total annual energy (electricity) consumption should be divided by the area of the buildings. Area of the buildings were calculated by cumulatively adding all areas of the different floors. The areas were calculated from building plans provided by the institutions. For buildings lacking design plans, a tape measure was used to measure the area of each floor which were cumulatively added together to obtain the total area of each building.

As state in section 2.1.1, to calculate buildings' energy efficiency, the BEI obtained from equation 2.1 were compared with benchmark values for colleges captured in Table 2.1. Buildings in institutions of higher learning were considered because in the benchmark and baseline are classified as similar in terms of energy consumptions. To convert annual electricity consumption for colleges, the value was converted from square feet to square meters by multiplying the value by a factor of 10.764. The value obtained was then divided into four quartiles and each building consumption placed in the quartile the consumption fitted (Mbogori *et al*., 2013).

### 3.2.2 Air change rate, ventilation rate and indoor air quality determination

Air change rate in the buildings was calculated using the build-up tracer gas method as shown in eqns. 2.4 and 2.5. Indoor and outdoor $CO_2$ concentration in parts per million (ppm) were measured across all buildings for a period of 4 months at an interval of 10 minutes between 11:00 am and 4:00 pm every weekday. The data was collected between November 2018 and February 2019. Since the build-up method was used to calculate the air change rate, the buildings were allowed time to achieve equilibrium concentrations to eliminate errors due to sharp increase in $CO_2$ concentration occasioned by increased occupancy. Metabolic $CO_2$ was used as a tracer gas in this study because it satisfies all conditions for tracer gas as specified in section 2.1.2. Starting the measurements at 11:00 am allowed the buildings enough occupancy time to achieve equilibrium. Vacating the measurements at 4:00 pm was to ensure no abrupt decline in concentration due to occupants leaving the building premises. All the four buildings were naturally ventilated and any air infiltration was as result of passive ventilations systems. Buildings ventilation rates were calculated using eqn. 2.6 by getting the product of air change rate and volume of the room or building occupied. The volume was calculated from the area measured or deduced from the design plans and the height of each floor and summed up together.

Temperature and humidity as other indoor environment parameters were measured simultaneously with $CO_2$ in each building. Temperature was recorded in degrees Celsius (℃) and humidity in percentage (%). The humidity and temperature were compared with ASHREA Standard to establish level of compliance of the buildings (Laue, 2018; McNulty *et al*., 2019). The three indoor air quality parameters measured were correlated to establish how each parameter affected concentration levels of the others.

### 3.2.3 Sustainability Testing

Sustainability testing for the green buildings was done for two categories; renewable energy and energy efficiency category and indoor health environment category as specified in the GreenMark Standard (Otieno, 2018). The testing involved use of the checklists for each category attached in Appendix 28 for renewable energy and energy efficiency and 29 for indoor health environment. Each building was assessed based on the characteristics specified in the checklists and weighting awarded depending on the level of compliance to the specified characteristics. The results are compared to establish how the green buildings perform based on the standard and if they would qualify as green buildings. The two categories carry a maximum of 20 points (marks) on the rating scale for GreenMark.

## 3.3 Sampling Method

This study utilized convenient sampling due to challenges of finding green buildings, Professional Bodies like Green Africa Foundation were critical in identifying green buildings in the country due to the few number of green buildings in the country. For comparability purposes, the researcher identified green buildings within learning institutions. To determine energy consumption, the researcher used one year's electricity consumption. Power bills provided by Kenya Power were used to calculate BEI. The BEI were compared with the benchmark and baseline values set by EPRA to establish the energy efficiency of each building. $CO_2$, temperature and humidity levels were measured for a period of 4 months between November 2018 and February 2019. Cumulative scores for all characteristics in each category for sustainability testing was used to establish building performance. The checklist used to award the scores was an excerpt from the GreenMark standard. Since the buildings were constructed before the GreenMark standard was established, the checklist was used to validate how the buildings would perform if subjected to the standard rating criteria.

## 3.4 Sample Size Determination

The study utilized two green buildings (GB1 and GB2) and two non-green buildings (NGB1 and NGB2); in each institution, one green and one non-green building were selected. Due to limited number of green buildings in the country and challenges to secure permission for more buildings, only four buildings were considered for this study. The non-green buildings (NGB1 and NGB2) were conventional buildings within the same institutions as the two green buildings. Using of population as the sample size is justified when the population is small and defined to reduce possibility of bias occurring when subjected to sampling techniques.

### 3.5 Research Instruments

Energy bills provided by Kenya Power to the institutions were used to determine energy consumption patterns of the buildings. Hard and digital copies were considered for the year 2018 from January to December. $CO_2$, temperature and relative humidity levels inside and outside the buildings were measured using a HT-2000 $CO_2$ meters (Fig. 3.2), (Digital Liquid Crystal Display (LCD) $CO_2$ meter), utilizing Nondispersive Infrared (NDIR) sensor which uses waveguide technology and has an automatic background calibration. The sensor records $CO_2$ concentration within a range of 0-9999 ppm manufactured by Dongguan Xintai Instrument Co. Ltd. The LCD measures $CO_2$ in ppm (parts per million), temperature (℃) and humidity (percentage). Energy consumption patterns were determined using electricity bills provided by the Kenya Power (KP). Power bills provide cheaper and easier way to establish energy consumption in buildings. Tape measure used in the buildings to measure the length, height and width of the buildings. Lastly, GreenMark rating tool checklists were used to rate the sustainability of selected green buildings. GreenMark standard checklist characteristics for the two categories considered in this study are as shown in Appendix 28, 29 and 30

**Figure 0.2: HT-2000 $CO_2$ Meter**

### 3.6 Data Processing and Analysis

Data processing and analysis was done using R studio and excel software. Energy intensity graphs drawn to analyze energy consumption patterns in the buildings. BEI intensities were calculated using eqn. 2.1 and compared with benchmark and baseline values established by EPRA to determine the buildings' energy efficiencies (Mbogori *et al*., 2013). Statistical analysis using excel was used to determine statistical significance difference between green building's energy consumption and non-green buildings. Excel software was used to draw graphs to find the airflow rates and correlation between $CO_2$ and temperature and humidity. From the excel graphs, the air change rate was taken as the gradient of the best line of fit as specified in eqn. 2.6. Mean $CO_2$, temperature and humidity values for the period under study were compounded to determine mean concentration, temperature and humidity levels. The mean values were also used in determining the air change rates and ventilation rates in the buildings. Pearson correlation between temperature, relative humidity and $CO_2$ concentrations were done to inform on how the indoor parameters interacted and affected indoor air quality. ANOVA was performed on the air change rates to determine significance variation between green and non-green buildings. Summation for checklist scores for each buildings were used to establish green buildings' performance in comparison to the GreenMark standard.

# CHAPTER FOUR

# RESULTS AND DISCUSSION

## 4.1 Energy consumption and Efficiency

### 4.1.1 Energy Consumption Patterns

The study used monthly energy consumption for the year 2018. GB1 lacked independent metering system to measure hence; energy consumption tracing was not possible. Additionally, GB1 powered by solar PV during the day and any power supplied during the night by Kenya Power compensated using the PPP packed signed by the Strathmore University and Kenya Power. GB2 had annual energy consumption of 399,016 kWh, with a range of 33,251.3 ± 3,462.3 kWh monthly. NGB1 had an annual energy consumption of 151,690 kWh, with a range of 11,778.7 ± 636.8 kWh. NGB2, on the other hand, had an annual energy consumption of 97,914.6 kWh with a range of 8,159.6 ± 120.6 kWh monthly as shown in Table 4.1 while monthly energy intensities are as shown in Fig. 4.1.

Energy intensities calculated using eqn.2.1. GB2 had mean monthly BEI of 2.6 ± 0.3 kWh/m$^2$ and annual BEI of 31.4 ± 0.3 kWh/m$^2$, NGB1 had mean monthly BEI of 4.4 ± 0.2 kWh/m$^2$ and annual BEI of 52.3 ± 0.2 kWh/m$^2$ and NGB2 had mean monthly BEI of 4.4 ± 0.1kWh/m$^2$ and annual BEI of 52.5 ± 0.1 kWh/m$^2$. Analysis of variance (ANOVA) at 95% confidence interval indicate significant statistical difference in energy consumption between GB2, NGB1 and NGB2 (p-value $=1.18\times10^{-12}$, df=33) while analysis of energy consumption between NGB1 and NGB2 are not significantly different (p-value= 0.7, df=22).

**Table 0.1: Building energy consumption patterns (N=12)**

| Building | Energy Range (kWh) | Annual energy consumption (kWh) | Monthly Consumption (kWh) | Area ($m^2$) | Annual BEI ($kWh/m^2$) | Monthly BEI $kWh/m^2$ |
|---|---|---|---|---|---|---|
| GB2 | 29081-39001 | 399016 | 33251.3 ±3462.3 | 12640.8 | 31.4 ±0.3 | 2.6 ±0.3 |
| NGB1 | 10784-12751 | 151690 | 11778.7 ±636.8 | 2701.1 | 52.3 ±0.2 | 4.4 ±0.2 |
| NGB2 | 7944.8-8351.5 | 97914.6 | 8159.6 ±120.6 | 1865.5 | 52.5 ±0.1 | 4.4 ±0.1 |

**Figure 0.1: Graphical presentation of BEI for the year 2018**

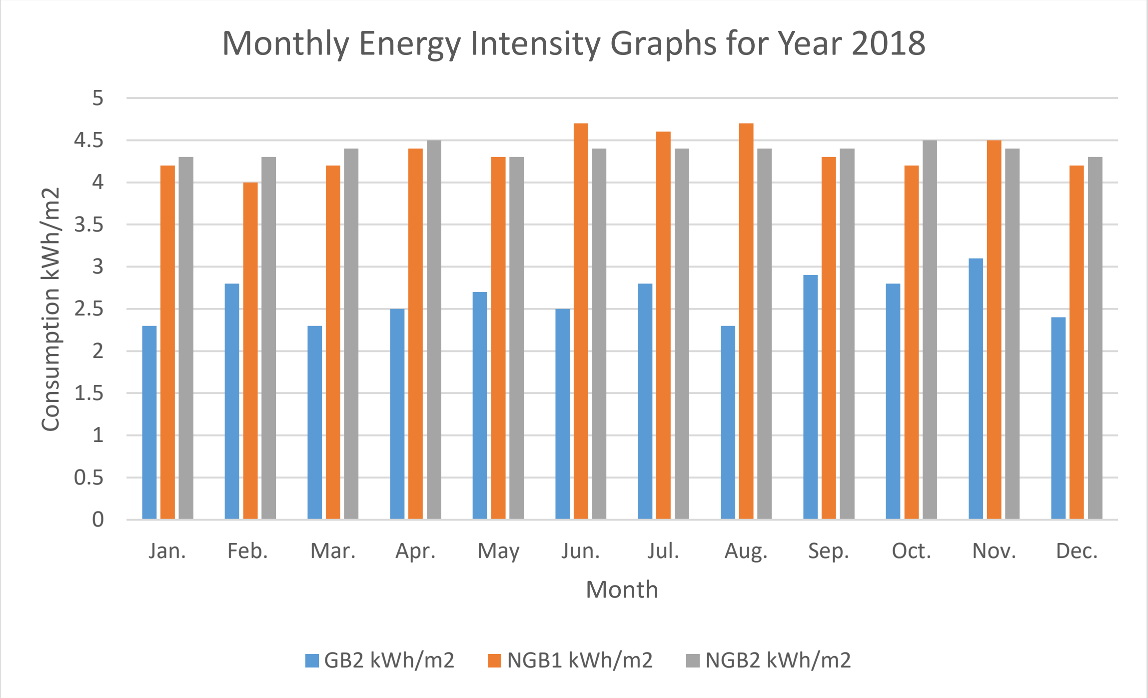


Fig. 4.1 shows that GB2 energy consumption is lower than that of NGB1 and NGB2 during the period of study. NGB1 and NGB2 energy consumption patterns varied during the period with alternating high and low for each building in different months. Additionally, consumption between NGB1 and NGB2 are close to each other and almost double consumption at GB2.

### 4.1.2 Building Energy Efficiency Intensities

Building energy efficiency is the energy consumption per unit area of a building compared to established consumption benchmarks. Kenya through the ministry of Energy and Petroleum developed Energy Management Regulation of 2012 to stipulated energy consumption benchmark for industrial, commercial and institutional buildings. Buildings can either be low, medium or high-energy consumers depending on their annual energy consumption. Total energy consumed in a building divided by the total floor area of the building gives the Building Energy Index (BEI) of the building. Low BEI indicates that a building is more energy efficient than those that have high BEI. Benchmarked and Baseline values for different kind of buildings are shown in Table 3.1. Annual BEI for the buildings are as shown in Table 4.2. Relating the annual BEI with the Benchmarked value divided into four quartiles ranks the energy intensities of the buildings into 1st and 2nd quartiles as shown in Table 4.2. 1st quartile represents the most efficient buildings while the 4th quartile represent the least efficient building (Mbogori *et al*., 2013).

**Table 0.2: Quartile classification of BEI in the buildings**

| | **1st quartile** | **2nd quartile** | **3rd quartile** | **4th quartile** |
|---|---|---|---|---|
| Benchmark value kWh/m$^2$ | 0-43 | 44-86 | 87-129 | 130-172 |
| GB2 | 31.4 ± 0.3 | | | |
| NGB1 | | 52.3 ± 0.2 | | |
| NGB2 | | 52.5 ± 0.1 | | |

Table 4.2 presents annual energy intensities for buildings GB2, NGB1 and NGB2 compared to the benchmark and baseline values by the EPRA (Mbogori *et al*., 2013). At 1st quartile, GB2 is more energy efficient than 75% of similar buildings while at 2nd quartile NGB1 and NGB2 are more energy efficient than 50% of similar buildings. Green building rating tools require buildings to use between 25-30% less than normal buildings and GB1 and GB2 use at least 40% less energy compared to buildings NGB1 and NGB2. Such low energy consumption in green buildings supports research by Nguyen and Aiello (2013), who established that green buildings should utilize less energy compared to conventional buildings.

Efficient energy consumption for GB1 and GB2 can be attributed to the green features such as day lighting and use of energy efficient light emitting diodes (LEDs) for lighting, which according to Howe (2010) should utilize energy efficiently. Research shows that most of energy in buildings is utilized in heating, cooling and lighting (Akadiri *et al*., 2012; Nguyen and Aiello, 2013), GB2 relies on passive heating and cooling of the building and natural lighting during the day, saving lots of energy that would have been used to power lighting, heating and cooling systems. Additionally, use of LEDs for lighting reduces energy consumption of the building. The major difference in terms of energy use in GB2 as opposed to NGB1 and NGB2 is use of day lighting at GB2 and artificial lighting in NGB1 and NGB2 during the day, in addition to some offices in NGB1 and NGB2 having air conditioning systems. According to Lowry (2016), use of day lighting can result to between 25% to 34% energy consumption savings while automating lighting systems in commercial buildings can yield about 40% of energy saving. In developed countries, lighting consumes between 11-17% of total energy consumed by commercial buildings (Allouhi *et al*., 2015). One of the major attribute of the green buildings sustainability is the energy efficiency, and GB1 and GB2 low energy consumption index indicate sustainability of the building, utilizing 40% less energy than buildings in similar category.

NGB1 and NGB2 energy consumptions lie in the 2nd quartile of the Benchmarked and Baseline values. At the 2nd quartile, the buildings perform better than 50% of its type and is slightly above average in energy use. The buildings at this range perform better than those at the 3rd and 4th quartiles, however, it performs lower than those at 1st quartile. Building retrofitting, use of energy saving lighting and management of energy can reduce the annual energy consumption. The building indicates that there exist opportunities for more energy saving activities such as day lighting and use of energy efficient lighting systems that are cheap (Ruparathna *et al*., 2016).

In temperate climates, green buildings are airtight to reduce energy losses from HVAC systems (Steinmann *et al*., 2017). However, in tropical regions like Nairobi Kenya, green buildings should tap natural resources like day lighting and favorable temperature conditions in the region to reduce energy used for lighting, heating and cooling (Rotimi and Kiptala, 2014), as this research shows green buildings are utilizing less energy for being less air tight. It is therefore paramount for engineers and architects to factor regional difference while designing green buildings.

## 4.2 Indoor Air Quality of Buildings

### 4.2.1 Adequacy of Ventilation

Comfortable thermal and indoor environment in buildings only achieved when buildings receive fresh air throughout. In this study, $CO_2$ was used as the tracer gas as per eqn. 2.5 and $CO_2$ concentration difference between the indoor and outdoor as a function of time used to calculate the air change rates in the buildings, providing the airflow rates necessary to establish ventilation rates of the buildings.

#### 4.2.1.1 Air change rates for the building facades

Air ventilation characteristics of the buildings are as shown in Table 0.3.

**Table 0.3: Air change rates and airflow rates**

| **Building** | **Range** | **Mean** | **Std.dev** | **air change rate ($h^{-1}$)** | **Volume ($m^3$)** | **Airflow rate ($m^3$/h)** |
|---|---|---|---|---|---|---|
| GB1 | 0.021-0.04 | 0.031 | ±0.011 | 0.031 | 19768 | 612.808 |
| GB2 | 0.05-0.07 | 0.058 | ±0.01 | 0.058 | 35424 | 2054.592 |
| NGB1 | 0.003-0.009 | 0.006 | ±0.003 | 0.006 | 11079.6 | 66.4776 |
| NGB2 | 0.006-0.009 | 0.008 | ±0.002 | 0.008 | 5223.6 | 41.7888 |

The air change rates were obtained using eqn 2.6 and described using graphs as shown in Appendix 15 to Appendix 27 and the mean air change rates tabulated as shown in Table 4.3. GB1 had air-change rate range of 0.21 $h^{-1}$ to 0.04 $h^{-1}$ with a mean of 0.031 ±0.011 $h^{-1}$. GB2 air change rate ranged from 0.05 $h^{-1}$ to 0.07 $h^{-}$1 with a mean of 0.058 ±0.01 $h^{-1}$. NGB1 had air-change rate range of 0.003 $h^{-1}$ to 0.009 $h^{-1}$ with a mean of 0.006 ±0.003 $h^{-1}$ while NGB2 had air-change rate range of 0.006 $h^{-1}$ to 0.009 $h^{-1}$ with a mean of 0.008 ±0.002 $h^{-1}$. According to Beko *et al*., (2016), low airflow rates indicate more airtight envelops than when buildings have higher air change rates. Buildings with low air change rates or low infiltration are susceptible to pollutant accumulation and contaminants exposure to the occupants (Beko *et al*., 2016). Therefore, occupants at NGB1 and NGB2 were more likely exposed to contaminants, pollutants and infections because the buildings have lower air change rates than GB1 and GB2. GB1 and GB2 had better airflow rates than NGB1 and NGB2. Although, low infiltration in NGB1 and NGB2 can reduce inflow of pollutants from outdoor, they pose the risk of increasing concentration of indoor pollutant emissions concentrations (Steinemann *et al*., 2017).

Air change rates in GB1 and GB2 were significantly different at 95% confidence interval (p-value = 0.01) as both have different ventilation systems adopted during construction and design phases. According to Aflaki *et al*., (2015), cross ventilation is more effective than stack ventilation, while a combination of both stack and cross ventilation systems enhances fresh airflow. Enhanced airflow rates at GB2 are attributable to enhanced cross ventilation due to presence of ventilation cowls on the roof of the building and ventilation louvers on the walls of the building absent at GB1. GB1 facade relies only on stack ventilation, which is less reliable than GB2 reliance on both cross ventilation and stack ventilation (Chel and Kaushik, 2018). Air change rate at GB1 was significantly different from NGB1 (p-value = 0.02) as airflow rates are influenced by temperature difference between indoor and outdoor. GB2 and NGB2 air change rates was also significantly different (p-value = 0.002). However, there was no significant difference in air change rates between NGB1 and NGB2 (p-value = 0.7).

#### 4.2.1.2 Air change rate for office blocks

Air change rates for office blocks within the buildings presented in Table 4.4 as derived from graphs in Appendix 1 to Appendix 14 calculated using eqn. 2.5. GB1 office block measured a length of 10.7m, width 8.1m and height of 2.8m, and volume of 242.7m$^3$. GB2 office block measured length of 6.6m, width 5.8m and height 2.8 m and volume of 107.2m$^3$. NGB1 office block had a length of 5.5m, width 2.1m and height 2.8m and volume of 32.3m$^3$.

Eqn 2.6 used for this study assumes absolute volume of the buildings without considering the equipment and objects. Comparing the airflow rate of the buildings and offices shows that the buildings performed below the expected airflow rate of between 18m$^3$/hr/person stated by the BSI and ASHREA standards (Laue, 2018; McNulty *et al*., 2019).

**Table 0.4: Air change rate for office blocks in the buildings**

| Building | Range ($h^{-1}$) | Mean | Std.dev | Air change rate($h^{-1}$) | Volume ($m^3$) | Airflow rate ($m^3$/hr) | Occupants | Airflow rate/person ($m^3$/hr/person) |
|---|---|---|---|---|---|---|---|---|
| GB1 | 0.013-0.48 | 0.353 | ±0.2 | 0.353 | 242.7 | 85.7 | 9 | 9.5 |
| GB2 | 0.011-0.139 | 0.058 | ±0.06 | 0.058 | 107.2 | 6.2 | 4 | 1.6 |
| NGB1 | 0.004-0.056 | 0.02 | ±0.02 | 0.02 | 32.3 | 0.7 | 2 | 0.35 |

GB1 office block had air-change rate range of 0.013 $h^{-1}$ to 0.48 $h^{-1}$, with a mean of 0.353 ±0.2 $h^{-1}$. GB2 office block had air-change rate range of 0.011 $h^{-1}$ to 0.139$h^{-1}$ and a mean of 0.058 ±0.06 $h^{-1}$. NGB1 had air-change rate range of 0.004 $h^{-1}$ to 0.056 $h^{-1}$ and a mean of 0.02 ±0.02 $h^{-1}$. All the office blocks had lower ventilation rate per person than the recommended a minimum of 18 $m^3$/hr/person and a maximum of 27 $m^3$/hr/person (McNulty *et al.*, 2019). GB1 office block had highest ventilation rate per person of 9.5 $m^3$/hr/person, followed by GB2 office block with 1.6 $m^3$/hr/person and 0.35 $m^3$/hr/person for NGB1.

There was significant difference in air change rates between GB1 office block and GB2 office block (p-value = 0.008), between GBI and NGB1 office blocks (p-value = 0.01). The office blocks for GB1 and NGB1 in Table 4.4 were closer to windows and compared to air change rate for GB1 and NGB1 shown in Table 4.4, are higher. The findings of this study supports Beko *et al.*, (2016) that window opening influence internal airflows in a room. GB2 office block had same air change rate as the building façade as shown in Table 4.3 and Table 4.4. GB2 walls had ventilation louvers, which excludes windows as the only openings through which air infiltration takes place. Although, GB1 had better air change rates, occupants complained of experiencing extreme weather conditions or ventilation draught, and air tightness could be linked to thermal energy leakages (Howe, 2010), hence workers in GB1 confided to experiencing thermal discomfort depending on the external conditions which could be related to higher airflow rates recorded in the office.

### 4.2.2 Effects of air change rates on $CO_2$, temperature and relative humidity

#### 4.2.2.1 $CO_2$, Temperature and Relative Humidity Variation

Table 4.5 contains results for indoor environmental variables. The $CO_2$ concentration for GB1 were in range of 527.7 ppm to 541.3 ppm with mean of 534.2 ± 3 ppm. GB2 $CO_2$ levels were in the range of 586 ppm to 620 ppm with a mean of 607 ± 7.9 ppm. NGB1 had $CO_2$ concentration range of 680.8 ppm to 696.1 ppm and mean of 689.2 ± 3.1. NGB2 had $CO_2$ concentration range of 689.4 ppm to 701.4 ppm with a mean of 695 ± 3.1 ppm. In all the buildings, $CO_2$ concentration was below the maximum 1000 ppm for quality indoor air. GB1 had temperatures range of 23.6 $^0$C to 25.1 $^0$C and mean of 24.4 ± 0.5 $^0$C, GB2 had temperatures range of 22.1 $^0$C to 23.6 $^0$C and mean of 22.9 ± 0.4 $^0$C. NGB1 had temperature range of 21.1 $^0$C to 24.2 $^0$C and mean of 22.9 ± 1 $^0$C while NGB2 had temperature range of 22.7 $^0$C to 22.2 $^0$C and mean of 25.4 $^0$C. GB1 had a relative humidity range of 54.4% to 56.4 % and mean of 55.2 ± 0.6 %, GB2 had relative humidity range of 50.4% to 54.7% and a mean of 51.8 ± 1.1%. NGB1 had relative humidity range of 57.8% to 58.8% and a mean of 58.3 ± 0.3% while NGB2 had relative humidity range of 59.7% to 60.8% and mean of 60.3 ± 0.3%.

$CO_2$ variation across the buildings as shown in Fig. 4.2, GB1 and GB2 have lower concentrations than NGB1 and NGB2. Lower ventilation rates in NGB1 and NGB2 could be associated with higher accumulation of $CO_2$ in the non-green buildings. Green buildings have higher airflow rate, hence remove $CO_2$ and other contaminants inside the buildings faster.

**Table 0.5: Buildings' Indoor characteristics (N=32)**

| Characteristics | Range | Mean | Std. dev |
|---|---|---|---|
| $CO_2$ Concentration (ppm) | | | |
| GB1 | 527.7 - 541.3 | 534.2 | ± 3 |
| GB2 | 586 - 620 | 607.6 | ± 7.9 |
| NGB1 | 680.8 - 696.1 | 689.2 | ± 3.1 |

|  |  |  |  |
|---|---|---|---|
| NGB2 | 689.4 - 701.4 | 695 | ± 3.1 |
| Temperature ($^{0}$C) |  |  |  |
| GB1 | 23.6 - 25.1 | 24.4 | ± 0.5 |
| GB2 | 22.2 - 23.6 | 22.9 | ± 0.4 |
| NGB1 | 21.1 - 24.2 | 22.9 | ± 1 |
| NGB2 | 22.7 - 27.2 | 25.4 | ± 1.4 |
| Relative Humidity (%) |  |  |  |
| GB1 | 54.4 - 56.4 | 55.2 | ± 0.6 |
| GB2 | 50.4 - 54.7 | 51.8 | ± 1.1 |
| NGB1 | 57.8 - 58.8 | 58.3 | ± 0.3 |
| NGB2 | 59.7 - 60.8 | 60.3 | ± 0.3 |

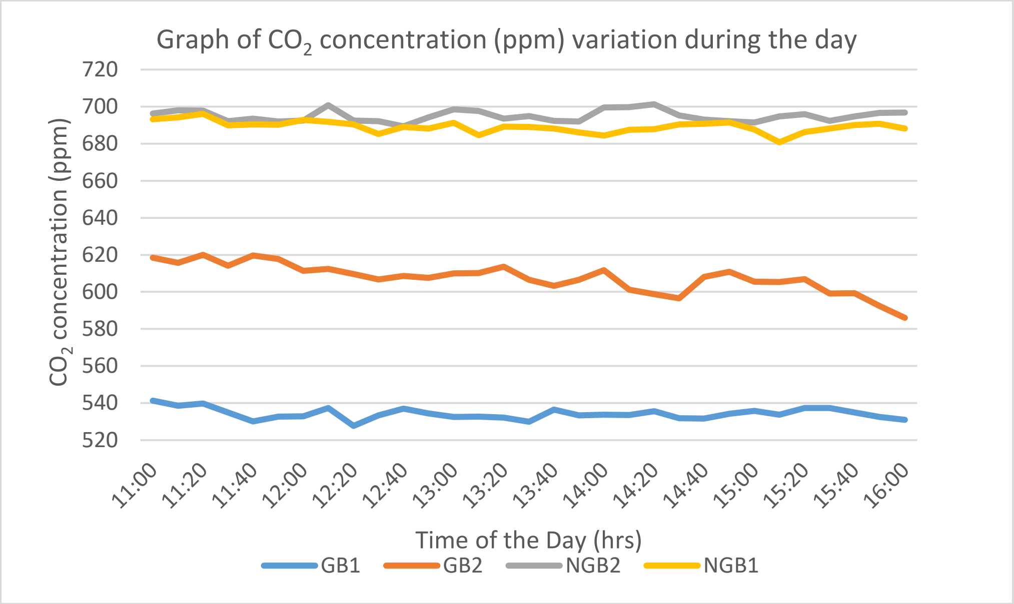


**Figure 0.2: Graphical presentation of $CO_2$ variation in parts per million**

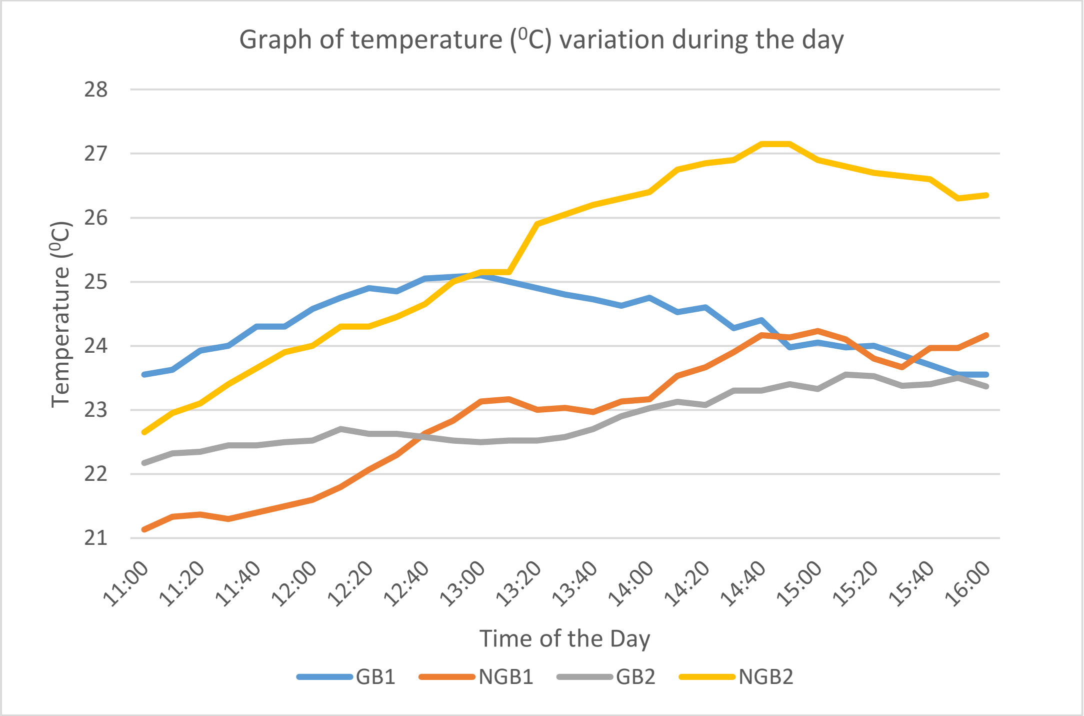


**Figure 0.3: Temperature in degree Celsius variation in the buildings**

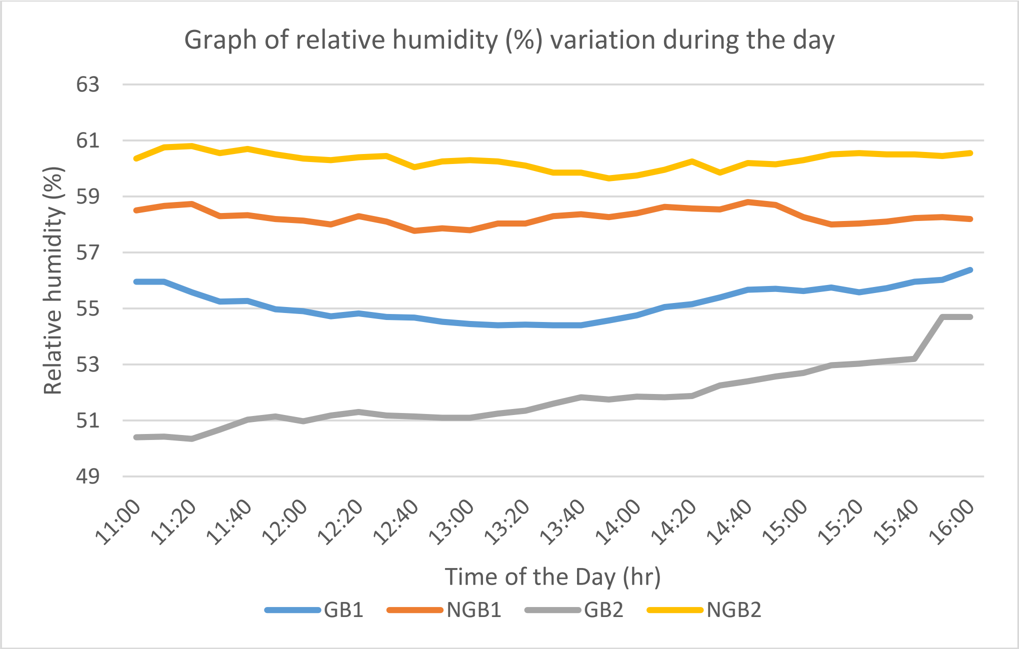


**Figure 0.4: Percentage Relative humidity variation**

Temperature levels in green and non-green buildings vary, however, comparing GB1 and NGB1, the temperatures are higher in GB1 than NGB1, which could be attributed to presence of water falls in GB1 resulting to higher sensible heat, than in NGB1 which has no waterfalls. High moisture content results in increased ambient temperatures (Seputra, 2018). In addition, GB1 temperatures dropped towards the end of day, an indication that the building materials has poor heat conservation properties. Use of glass curtain wall at GB1 contribute to quick heat gain and loss depending on the external conditions (Liu and Cui, 2015). GB2 and NGB2 temperature changes show gradual increase, although, temperatures were lower in GB2, attributable to higher ventilation rates. NGB2 temperature increased beyond the recommended maximum of 27℃ for thermal comfort (Seputra, 2018). Relative humidity, an attribute of thermal comfort varies different with GB2 recording the lowest relative humidity as shown in Fig. 4.4 and NGB2 had the highest level of humidity. Both NGB1 and NGB2 had relative humidity near or above the maximum thermal comfort level of 60% (Seputra, 2018). Higher ventilation rates in GB1 and GB2 could be associated with accelerated removal of humidity inside the buildings.

#### 4.2.2.2 Statistical analysis of $CO_2$, Temperature and Relative Humidity in the buildings

Statistical analysis of variation (ANOVA) for $CO_2$, temperature and relative humidity within the buildings as shown in Table 4.6. Comparing buildings in the same institution, there was significant difference in $CO_2$ concentration, temperature and humidity levels (significant for $p$-value $< 0.05$) as shown in Table 4.6. GB1 had significantly lower $CO_2$ concentration and relative humidity than NGB1 (p-value = $2.02\times10^{-86}$ and p-value = $1.06 \times 10^{-34}$ respectively), though GBI had significantly higher temperatures than NGB1 (p-value = $2.62\times10^{-09}$). Such differences are attributable to ventilation rates of the two buildings as discussed earlier. GB2 had significantly lower $CO_2$, temperature, and relative humidity than NGB2 (p-value= $3.34\times10^{-54}$, p-value = $7.45\times10^{-14}$ and p-value= $1.79\times10^{-45}$ respectively). GB2 has enhanced ventilation rates due to removal of $CO_2$, temperature and relative humidity faster than NGB2.

**Table 0.6: Institutional variation in indoor air conditions**

| Parameter | Values | | p-value | Value | | p-value |
|---|---|---|---|---|---|---|
| | GB1 | NGB1 | | GB2 | NGB2 | |
| $CO_2$ (ppm) | 534.2 | 689.2 | **2.02E-86** | 607.6 | 695 | **3.34E-54** |
| Temp. ($^0$C) | 24.4 | 22.9 | **2.62E-09** | 22.9 | 25.4 | **7.45E-14** |
| RH (%) | 55.2 | 58.3 | **1.06E-34** | 51.8 | 60.3 | **1.79E-45** |

Performing t-test gives the Pearson Correlation (r) of how different indoor environment parameters interact within each building. Temperature significantly and negatively correlated with relative humidity, across all the buildings (r = -0.94 at GB1, r = -0.01 for NGB1, r = -0.48 for NGB2) except at GB2 (r= 0.89), as result of effective ventilation at GB2. Generally, at constant vapor content, increase in temperature results in decrease in relative humidity as shown by this study and findings by Feng *et al*., (2018). Mean daily $CO_2$ levels correlates positively and significantly with relative humidity across all buildings (r = 0.27 for GB1, r = 0.39 for NGB1 and r = 0.04 for NGB2) except for GB2 which negatively and significantly correlate with relative humidity (r = -0.83). The finding of this study agree with the findings by Nnadili that increasing relative humidity results in increased concentration of $CO_2$ and other VOCs (Nnadili, 2011). In addition, other researchers have found that increase in temperature and humidity results to off-gassing from equipment, electronics, furniture, books and paints in the buildings (Laverge *et al*., 2015; Haung *et al*., 2016; Lazovic *et al*., 2016; Steinemann *et al*., 2017). These authors found that when relative humidity in the indoor increased, such translated to increasing $CO_2$ concentrations, similar to the findings of this study. According to Lazovic *et al*., (2016), off gassing could be addressed by improving ventilation rates of the buildings and such findings are supported by the negative and significant difference exhibited by GB2 to both relative humidity and temperatures. The authors further noted that improving ventilation rates reduces the impact of exposure to $CO_2$ and other VOCs. All buildings show negative and significant correlation between $CO_2$ and temperature, (r = -0.36 for GB1, r = -0.51 for NGB1 and r = -0.72 for GB2). The results of this study suggest that lower temperatures trigger increase in metabolic $CO_2$ production, which supports findings by Blondin *et al.,* (2017), that cold induces oxidative metabolism, resulting to exhalation of $CO_2$ by human beings. Significant correlation between $CO_2$ concentrations and other indoor air quality parameters (relative humidity and temperature) poses challenges on indoor air quality because, though $CO_2$ in low amounts might not affect people, it signifies possibility of increasing exposure to contaminants and pollutants (Cetin, 2016; Yalcin *et al*., 2016).

## 4.3 Sustainability Testing

Weighting awarded for every characteristic based on the GreenMark Standard and evidence obtained from the buildings in consideration. Sustainability testing was done for only the green buildings selected for this study and only two categories are considered for this study (Renewable energy and energy efficiency EE and Indoor health environment HE), as they directly relate with the objectives of the study.

**Table 0.7: EE GreenMark Score Weighting for GB1**

| Code | Characteristic | Evidence | Weighting | Comments |
|---|---|---|---|---|
| EE1 | Optimize Energy Performance | Entirely relying on renewable energy qualifies the building a NZEB | 2/2 marks | Good |
| EE2 | Commissioning and recommissioning of building Energy Systems | Natural ventilation effective.<br>Natural lighting controls<br>Water heating system effective<br>Renewable energy systems effective (Solar energy installed) | 2/2 marks | Good |
| EE3 | Energy Efficient Equipment, appliances, fittings | Use energy saving lighting systems.<br>Approved energy saving lifts by ERC<br>Use of Laptops rather than Desktops in offices.<br>Automated entrance<br>Use of electronic ballasts for lighting ranging between 14-28 watts.<br>Use of light-emitting diodes (LED) for lighting | 6/6 marks | Good |
| EE4 | Light Zoning | The building has well positioned lighting systems.<br>Has auto-sensor lighting | 2/2 marks | Good |
| EE5 | Renewable Energy | Use of solar power in the buildings to supplement utility power, producing 600kwh. | 5/5 marks | Good |
| EE6 | Energy Monitoring | Other than the net-metering intended for establishing the amount of renewable energy produced, no other energy control used. | 0.5/ 3 mark | poor |
| Total | | | 17.5/20 | Good |

GB1 energy performance based on the GreenMark Standard as shown in Table 4.7. It could be attributed to the LEED standard emphasize on energy savings and performance that was used to rate and design the building (Bahaudin *et al.*, 2014). Looking at the GreenMark Standard and the LEED Standard, they almost look alike on the categories and scoring system adopted. Based on the standard, GB1 lacks energy monitoring systems that can inform on energy consumption patterns and energy saving opportunities. On energy sustainability, GB1 has little improvement required to meet the GreenMark Standard criteria.

**Table 0.8: EE GreenMark Score Weighting for GB2**

| Code | Characteristic | Evidence | Weighting | Comments |
|---|---|---|---|---|
| EE1 | Optimize Energy Performance | Energy consumption calculated from this study indicate that the buildings consumes more than 40% from similar buildings as established ERPA 2013 Energy Performance Baseline and Benchmarks for Learning Institutions | 2/2 Marks | Good |
| EE2 | Commissioning and recommissioning of building Energy Systems | Natural ventilation effective.<br>Natural lighting controls<br>No Water heating system<br>Renewable energy systems (Uses wind to run ventilation cowls) | 1/2 marks | Fair |
| EE3 | Energy Efficient Equipment, appliances, fittings | Use energy saving lighting systems.<br>Approved energy saving lifts by EPRC<br>Combined Use of Desktops and laptops in the offices<br>Automated entrance | 4/6 marks. | Fair |
| EE4 | Light Zoning | Building has well positioned switches for individual and collective on and off switching of the building lights<br>Lacks auto-sensor lighting | 1/2 mark | Fair |
| EE5 | Renewable Energy | No direct renewable energy installed in the building. However, use of wind energy to drive ventilation cowls minimize energy use. Entirely relies on national utility power. | 1/5 mark | Poor |
| EE6 | Energy Monitoring | Lacks any energy monitoring systems other than whole building metering system | 1/3 marks | Poor |
| Total Score | | | 10/20 | Fair |

For GB2, renewable energy and energy efficiency category of the GreenMark standard as shown in Table 4.8. Although the building consumes energy efficiently as shown Fig. 4.1, based on GreenMark Standard, the building performance is poor because it lacks renewable energy source in place as stated in Code EE5. GB2 lacks auto-sensing lighting systems for the artificial lighting an important aspect of green buildings energy performance. Furthermore, the building lacks energy monitoring systems that can inform building occupants of the energy use patterns and energy conservation measures. Therefore, further investment on renewable energy and energy conservation measures should be implemented to meet the GreenMark Standards. Statistical analysis of variance between GB1 and GB2 energy consumption shows that there was no significant difference in energy performance for GB1 and GB2 (p-value =0.24).

**Table 0.9: HE GreenMark Score Weighting for GB1**

| Code | Characteristic | Evidence | Weighting | Comments |
|---|---|---|---|---|
| HE1 | Natural Ventilation, heating and Cooling, air change effectiveness | Shows moderate ventilation due to low airflow rates in the interior of the building and high airflow rates causing draught in the office.<br>South-North orientation to avoid direct solar heating. | 3/6marks. | Good |
| HE2 | User-friendly ventilating, heating and cooling systems | Environmentally adapted natural ventilation, hence user friendly. Also uses evaporative coolers, in addition to waterfalls to cool the building. Mass walls for heat retention to warm the building.<br>Windows fitted into the wall for shading, overhanging roof for solar heating and radiation. Slab roofing coated to reflect solar radiation reducing heat gain. | 1/1 mark | Good |
| HE4 | Natural lighting | Glass wall curtain and windows for illumination. Reflective roofing allows for adequate natural lighting through the atrium. Indoor light-coloured painting also enhances lighting by reflecting the sunlight through the building. | 3 /3marks. | Good |
| HE5 | User-friendly Lighting Systems | Automated lighting Systems detect when adequate natural lighting is available. | 1/1 mark. | Good |
| HE6 | Glare control and view out | Glass curtain walling allow for effective glare and view out. To reduce sun glare, the glazed roof of the atrium has aluminium aerofoil louvers to cut of glare and sunshade sunlight entering the building. | 1/1 mark. | Good |
| HE7 | Efficient Artificial Lighting Fittings | Fitted with 14-28 watts' florescent tube lightings with electronic ballast for artificial lighting purposes. White colour interior to enhance artificial lighting. | 3/3 marks. | Good |
| HE8 | Tobacco Smoke Control | No smoking signs<br>No smoking zones near the building. | Prerequisite | |
| HE9 | Indoor air quality testing and monitoring | No monitoring and testing of indoor air quality done. | 0/2 marks. | Poor |
| HE10 | Damp and mould prevention | In addition to using moisture-damping material during construction, natural ventilation keeps the humidity levels low in the building to prevent any moisture build up. | 1/1 mark | Good |
| HE11 | Internal Noise Level | Cafeteria has hanging fabrics to absorb noise. Other regions have decorated art that has fabric meant for noise absorption. | 0.5/1 mark | Fair |
| Total | | | 13.5/20 | Above |

average

GB1 health environment performance based on the characteristics stipulated in the GreenMark Standard as shown in Table 4.9. Major components of ensuring indoor air quality is maintained lack. The ventilation system is not effective as the interior has low airflow rates, as shown in Table 4.3 while the offices along the walls experience high airflow rates as shown in Table 4.4. Such variation in airflow rates result in ventilation draught to office occupants while the interior space is prone to pollutant and contaminant accumulation. Green buildings should have air quality monitoring and testing systems, which lack entirely in the building.  The building noise control system consisting of hanging fabrics and decorated art with fabric is not sufficient to regulate noise level in the building.

GB2 health environment performance as shown in Table 4.10. The building relies entirely on natural ventilation to supply fresh air inside the building. It has ventilation cowls (cyclones) fitted on the roof to facilitate airflow inside the building. In addition, along the walls, the building has ventilation louvers, which increase openings for indoor air to flow indoor. The building also relies on natural lighting during the day, though it lacks automated artificial lighting systems and light sensing system to switch on and off lights when needed. The building has an elaborate Noise control effected especially in the conference hall. Acoustic designs such as sound reflectors for speech clarity, use of sinusoidal walls to minimize multiple reflections, use of double cavity walls filled with mineral wool without cement mortar to reduce sound reflection, padding of internal columns with thick foam covered with vinyl for fire resistance. The ceiling has perforated plywood, mineral wool and hessian cloth for reducing sound reflection. Although it lacks indoor air quality and testing systems, it has mosquito and insect proof to prevent insects and dust from entering the building.

Statistical analysis of variance between the two buildings indicate that there was no significant difference between health indoor environment performance for GB1 and GB2 (p-value = 0.6)

**Table 0.10: HE GreenMark Score Weighting for** GB2

| **Code** | **Characteristic** | **Evidence** | **Weighting** | **Comments** |
|---|---|---|---|---|
| HE1 | Natural Ventilation, heating and Cooling, air change effectiveness | Performs exemplary.<br>Shows effective ventilation, uniformity- air change effectiveness enhanced by ventilation cowls, stack effect and chimneys, perforated openings and proper window to wall ratio. South-North orientation to avoid direct solar heating. | 6/6 marks. | Good |
| HE2 | User-friendly ventilating, heating and cooling systems | Environmentally adapted natural ventilation, hence user friendly. Use of rock bed responsible for cooling air during the day and warming during the night. | 1/1 mark. | Good |
| HE4 | Natural lighting | Windows and the atrium positioned to allow maximum natural lighting in the building. Indoor painting also enhances lighting by reflecting the light allowed in the building.<br>Sun shading using concrete over-hangings for all glazed areas to prevent direct sunlight. | 3/3 marks | Good |
| HE5 | User-friendly Lighting Systems | Lighting done manually, switched off in the morning and afternoon and switched on between 5:00 pm and 10:00 pm | 0.5/1 mark. | Fair |
| HE6 | Glare control and view out | Windows and doors allow for effective glare and outside view. To reduce sun glare, the glazed roof of the atrium has aluminium aerofoil louvers to cut of glare and sunshade sunlight entering the building. | 1/1 mark. | Good |
| HE7 | Efficient Artificial Lighting Fittings | Has low wattage florescent tubes for lighting. Light-coloured interiors to enhance artificial lighting. Use of LED for lighting purposes. | 3/3 marks. | Good |
| HE8 | Tobacco Smoke Control | No smoking zones visible in the nearby and No smoking warning visible. | Prerequisite | |
| HE9 | Indoor air quality testing and monitoring | Lacks air quality testing and monitoring systems. Mosquito and insect proof wire gauze openings to prevent insects and dust from entering the building. | 1/2 marks | Fair |
| HE10 | Damp and mould prevention | Damp prevention considered during construction. Proper natural ventilation preventing any moisture build up in the building. | 0.5/1 marks. | Fair |
| HE11 | Internal Noise Level | Noise control effected especially in the conference hall. Acoustic designs such as sound reflectors for speech clarity, use of sinusoidal walls to minimize multiple reflections, use of double cavity walls filled with mineral wool without cement mortar to reduce sound reflection, padding of internal columns with thick foam covered with vinyl for fire resistance. The ceiling has perforated plywood, mineral wool and hessian cloth for reducing sound reflection. | 1/1 mark. | Good |
| Total | | | 17/20 | Good |

# CHAPTER FIVE

# CONCLUSION AND RECOMMENDATION

## 5.1 Conclusion

The study sought to determine energy and indoor air quality performance for green and non-green buildings and test green buildings' sustainability using the GreenMark standard. The study shows that GB2 had BEI of 2.6 ± 0.3 kWh/m$^2$ and annual BEI of 31.4 ± 0.3 kWh/m$^2$ for the year 2018 compared to NGB1 mean monthly BEI of 4.4 ± 0.2 kWh/m$^2$ and annual BEI of 52.3 ± 0.2 kWh/m$^2$ and NGB2 mean monthly BEI of 4.4 ± 0.1kWh/m$^2$ and annual BEI of 52.5 ± 0.1 kWh/m$^2$. Hence, there was significant difference in energy consumed by green buildings and energy consumed by non-green buildings (p-value =1.18E-12), while there was no significant difference in energy consumption by non-green buildings, NGB1 and NGB2, (p-value = 0.7). Based on Energy Performance Benchmark and Baseline Values set by ERPA of 2013, GB2 energy performance lies in the 1st quartile while NGB1 and NGB2 energy consumption lies in the 2nd quartile. Buildings whose energy consumption lies in the 1st quartile are the most energy efficient than those in the preceding quartiles, with those in 4th quartile being the least energy efficient. Few and expensive opportunity for improving energy efficiency for buildings at 1st quartile exists, however, energy savings mechanisms such as use of renewable energy, energy efficient appliances and equipment, and building retrofitting can achieve sufficient energy saving for non-green buildings.

Indoor air quality is an important aspect of the built sector as people spend 90% of the time indoors (Feng *et al.*, 2018). The study shows that green buildings had superior air change rates, with GB1 mean air change rate of 0.031 ±0.011 h$^{-1}$, GB2 had mean air change rate of 0.058 ±0.01 h$^{-1}$ to non-green buildings, as NGB1 had mean air change rate of 0.006 ±0.003 h$^{-1}$ while NGB2 had mean air change rate of 0.008 ±0.002 h$^{-1}$. Statistical analysis of buildings in the same institution shows that there existed statistical significance in air change rate in the buildings; with air change rate at GB1 being significantly different from NGB1 (p-value = 0.02) and GB2 and NGB2 air change rates being significantly different (p-value = 0.002). Air change rate statistical significance between the GB1 and GB2 (p-value = 0.01) indicates effectiveness of ventilation louvers and ventilation cowls (cyclones) installed at GB2.

Indoor air quality parameters varied differently in each building. GB1 had temperature mean of 24.4 ± 0.5 $^0$C while GB2 had temperature mean of 22.9 ± 0.4 $^0$C. NGB1 had temperature mean of 22.9 ± 1 $^0$C while NGB2 had temperature mean of 25.4 $^0$C. GB1 had a relative humidity mean of 55.2 ± 0.6 %, GB2 had relative humidity mean of 51.8 ± 1.1%. NGB1 had relative humidity mean of 58.3 ± 0.3% while NGB2 had relative mean of 60.3 ± 0.3%. GB1 had significantly lower $CO_2$ concentration and relative humidity than NGB1 (p-value = $2.02\times10^{-86}$ and p-value = $1.06\times10^{-34}$ respectively), though GBI had significantly higher temperatures than NGB1 (p-value = $2.62\times10^{-09}$). GB2 had significantly lower $CO_2$ concentrations, temperature level, and relative humidity than NGB2 (p-value = $3.34\times10^{-54}$, p-value = $7.45\times10^{-14}$ and p-value = $1.79\times10^{-45}$ respectively). $CO_2$ correlates positively and significantly with relative humidity across all buildings (r = 0.27 for GB1, r = 0.39 for NGB1 and r= 0.04 for NGB2) except for GB2 which negatively and significantly correlate with relative humidity (r=-0.83), which could be attributed off gassing from equipment, books and metabolism from occupants.

Indoor air parameters correlated in each building to establish the interactions. Temperature significantly and negatively correlated with relative humidity, across all the buildings (r = -0.94 at GB1, r= -0.01 for NGB1, r = -0.48 for NGB2) except at GB2 (r=0.89). All buildings show negative and significant correlation between $CO_2$ and temperature, (r=-0.36 for GB1, r=-0.51 for NGB1 and r=-0.72 for GB2). Lower temperatures trigger increase in metabolic $CO_2$ production (Blondin *et al*., 2017).

Subjecting the two green buildings to sustainability testing using the GreenMark Standard yields different results for the two categories considered. GB1 renewable and energy efficiency (EE) category scores 17.5 out possible 20 points, majorly due to presence of renewable energy resource and automation of lighting and other components and wash-rooms in the building. However, Health Environment (HE) score lower marks of 13.5 out possible 20 points generally due to lack of indoor air quality testing and monitoring systems and poor noise level control and poor ventilation rates in the building, especially due to ventilation draught in the offices. For GB2, EE category performs poorly scoring 10 points of possible 20 points, especially due to lack of on-site renewable energy source and lack of automation of energy systems in the building. HE for GB2 scores 17 points out of possible 20 points. However, there was no significant difference in the energy performance and indoor health performance between GB1 and GB2 (p-value = 0.24 and p-value = 0.6 respectively).

## 5.2 Recommendations

As the study shows, green buildings are better energy users and have better indoor air conditions, therefore the government should focus on offering incentives, tax holidays and rebates to promote green building technology in the country. Further, government should push in policy formulation for construction sector as urban planning systems in existence today might impair development of green structures. Recent outbreak of COVID-19 pandemic should push all stakeholder to consider the importance of sustainable built environment.

Areas of further research include using other methods like door blower test to compare the results with those of the tracer gas method in determination of airflow rates in the buildings. Tracer gas method might be limited when openings in the buildings are manipulated to gain the rate of airflow in the buildings. Further research should also be undertaken on building material thermal comfort and which materials fits the local environment for green buildings.

Current spread of COVID-19 pandemic has increased concerns on built environment contribution to public health of the occupants. Engineering control systems such as ventilation and air circulation mechanisms have shown great impact on reducing airborne infections in buildings in the past. Research shows high infection rates in poorly ventilated buildings or buildings with air condition systems that recirculate the conditioned air (Morawska *et al*., 2020). Levels of infections in naturally ventilated buildings are significantly lower (Anderson *et al*., 2020). Results of this study show that indoor air quality can improve greatly on adoption of green buildings in the country. The results show 86.2% better air change rate in GB2 compared to NGB2. Similarly, 80.6% better air change rate in GB1 compared to NGB1. It is then clear that an infectious person would likely infect other people in the non-green buildings compared to green buildings.

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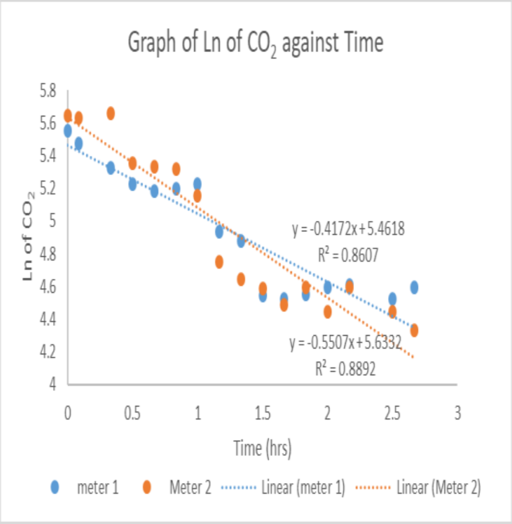
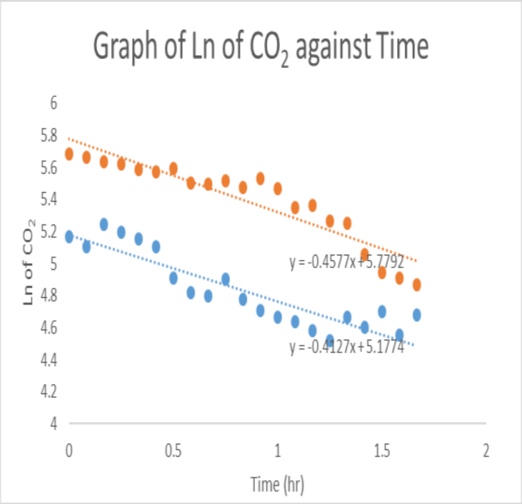
# APPENDICES

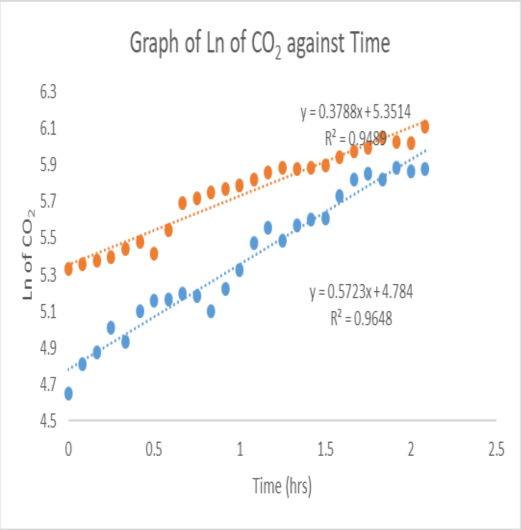
## Appendix I: Air change rate at GB1 office with window opened



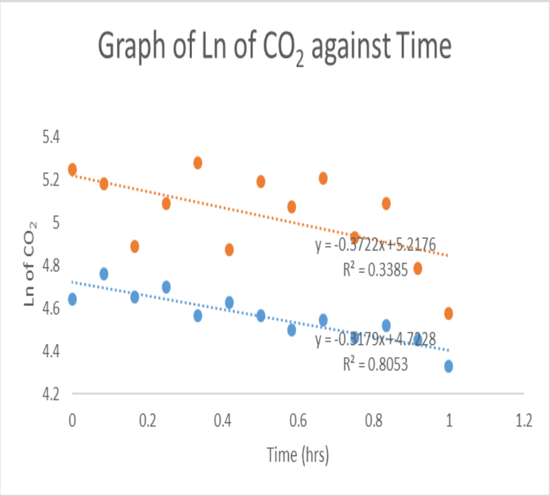
## Appendix II: Air change rate at GB1 office with window opened



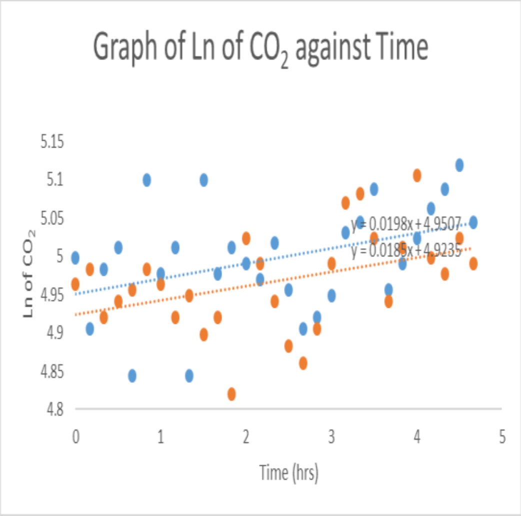
## Appendix III: Air change rate at GB1 office with window closed



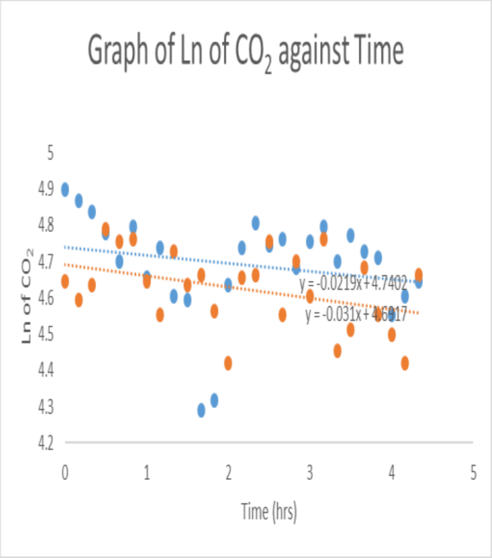
## Appendix IV: Air change rate at GB1 office during Lunch Break



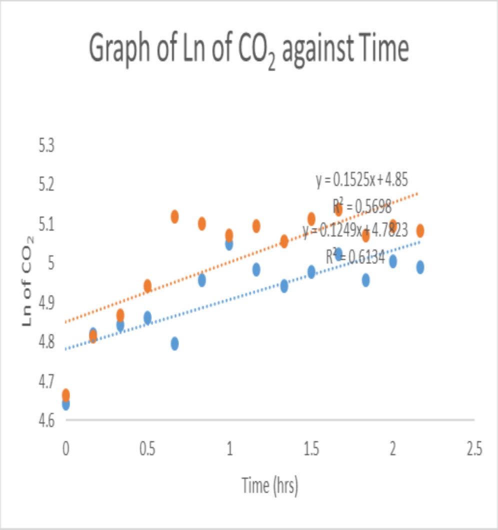
## Appendix V: Air change rate at GB2 office normal operation



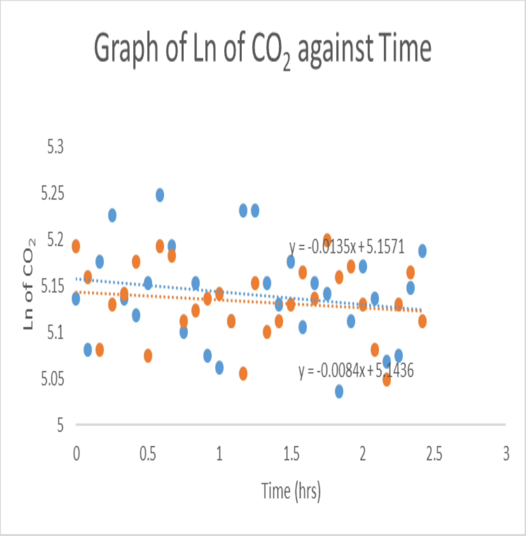
## Appendix VI: Air change rate at GB2 office with window opened



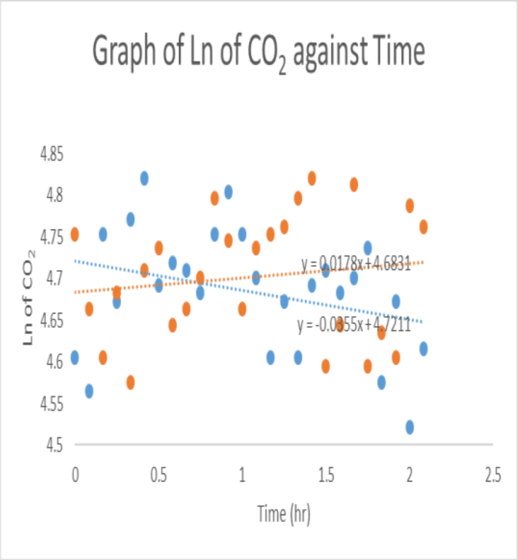
## Appendix VII: Air change rate at GB2 office with window closed



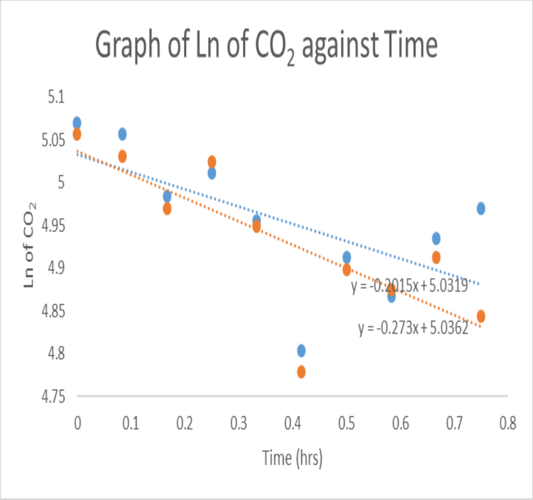
## AppendixVIII: Air change rate at GB2 office with window opened



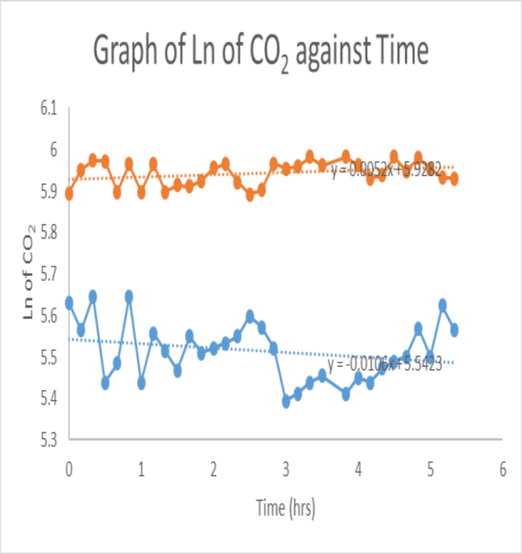
## Appendix IX: Air change rate GB2 office with window opened



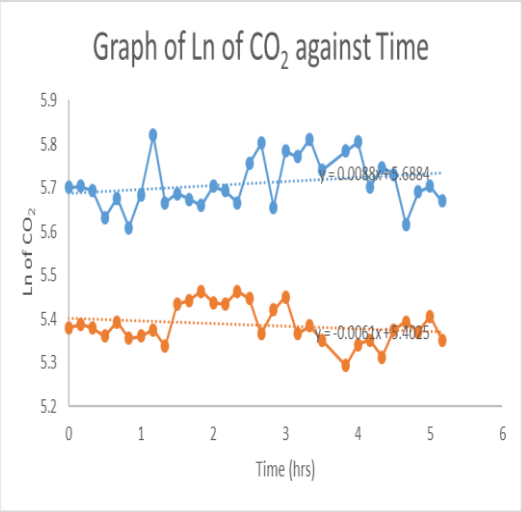
## Appendix X Air change rate at GB2 office with window opened



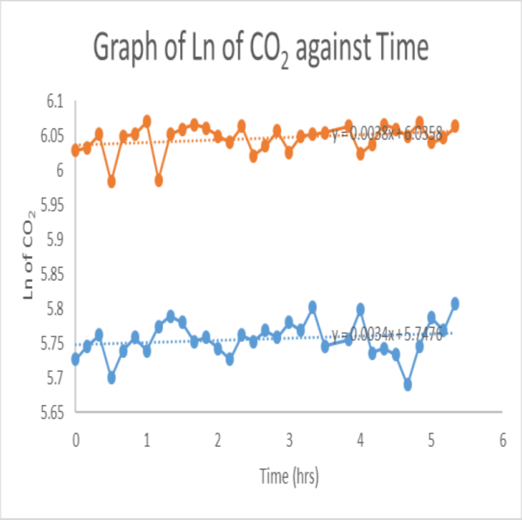
## Appendix XI: Air change rate at NGB1 office



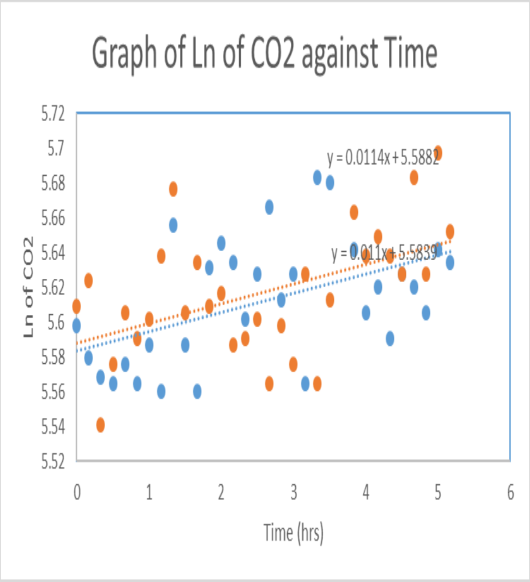
## Appendix XII: Air change rate at NGB1 office



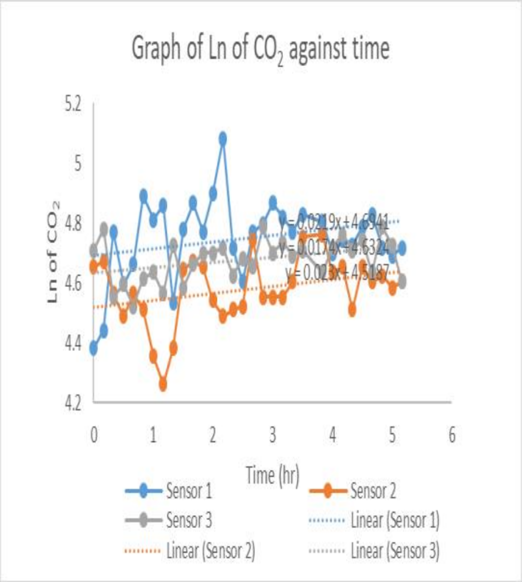
## Appendix XIII: Airflow rate at Building C office



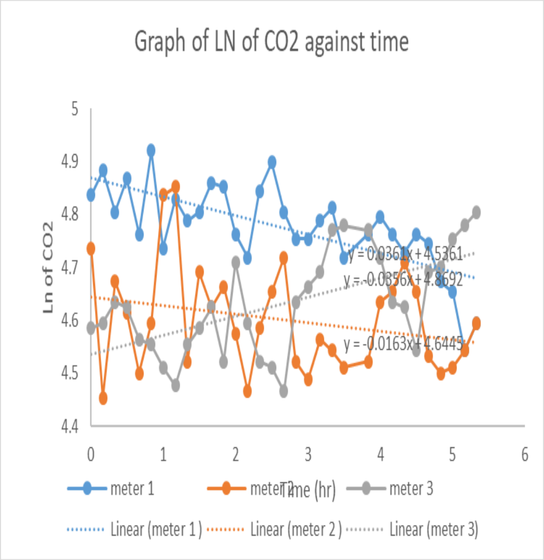
## Appendix XIV: Air change rate NGB1



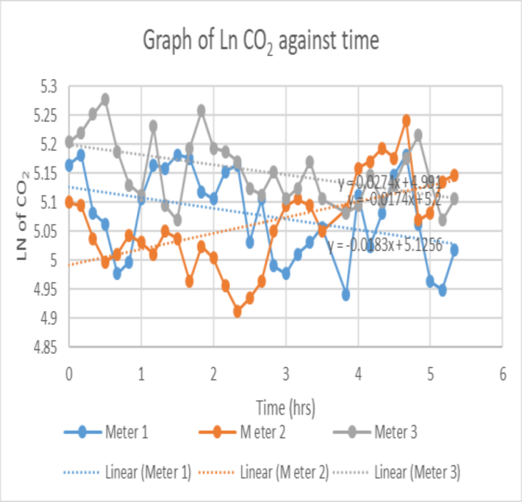
## Appendix XV: Air change rate GB1



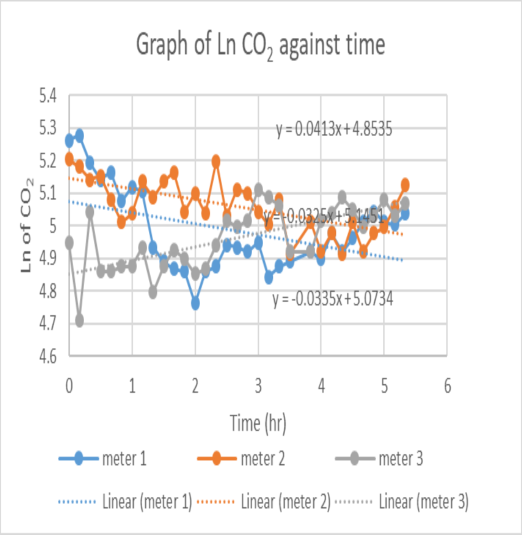
## Appendix XVI: Air Change rate GB1



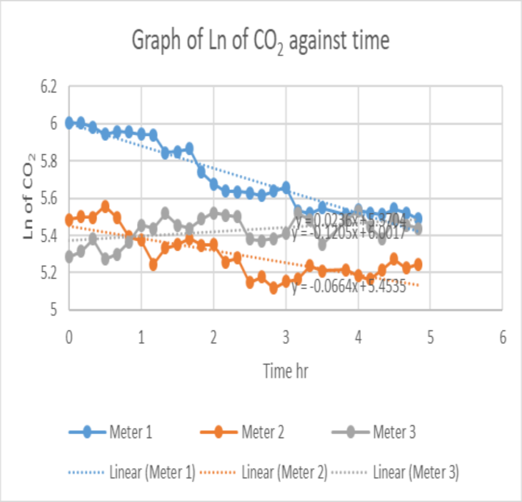
## Appendix XVII: Air change rate GB1



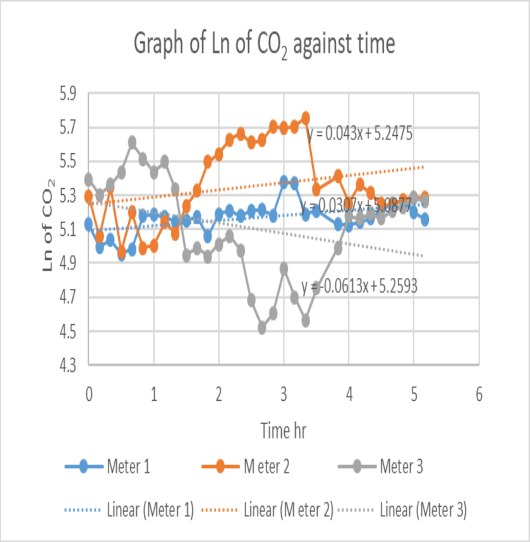
## Appendix XVIII: Air change rate GB1



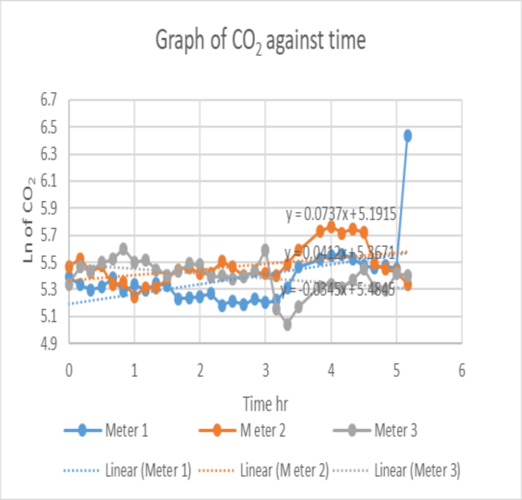
## Appendix XIX: Air change rate GB2



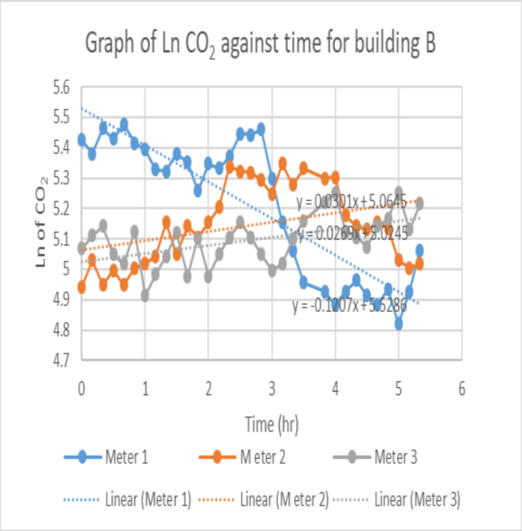
## Appendix XX: Air change rate for GB2



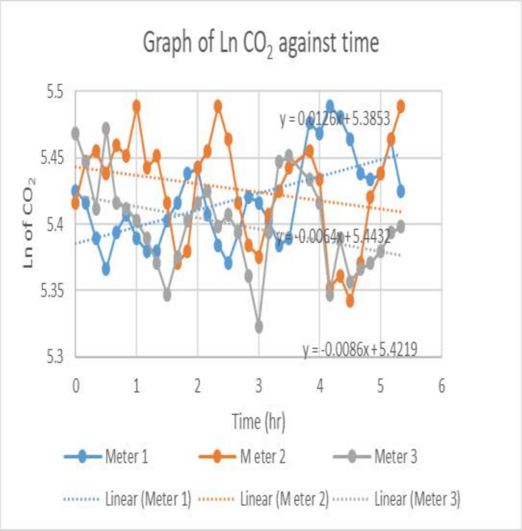
# Appendix XXI: Air change rate for GB2



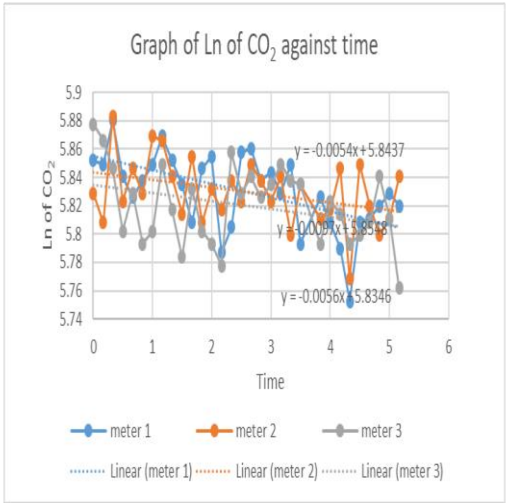
# Appendix XXII: Air change rate for GB2



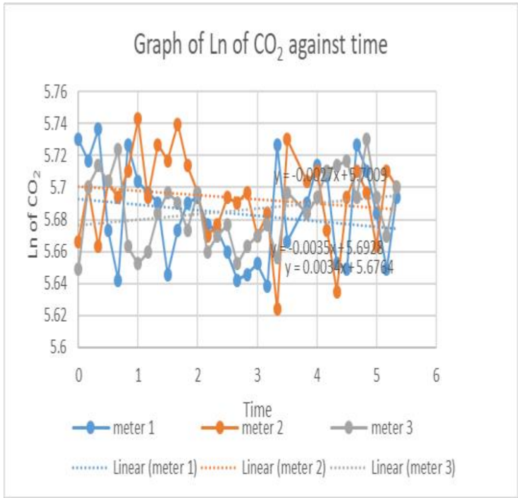
## Appendix XXIII: Air change rate for GB2



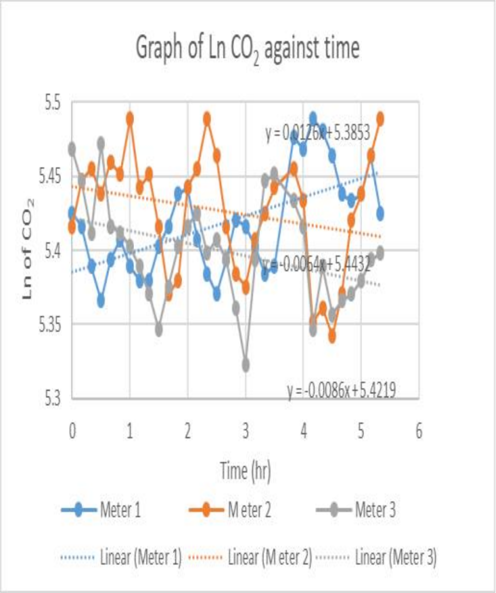
## Appendix XXIV: Air change rate for NGB1



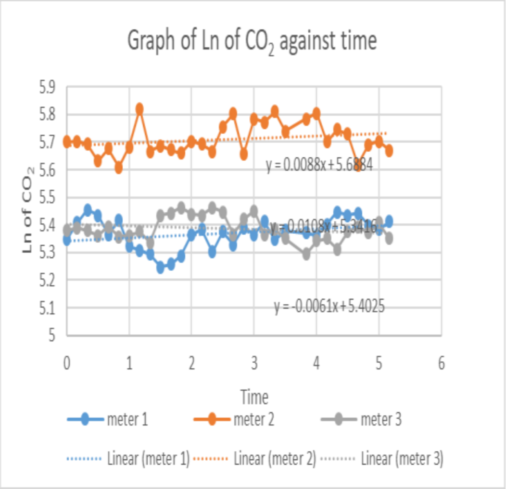
## Appendix XXV: Air change rate for NGB1



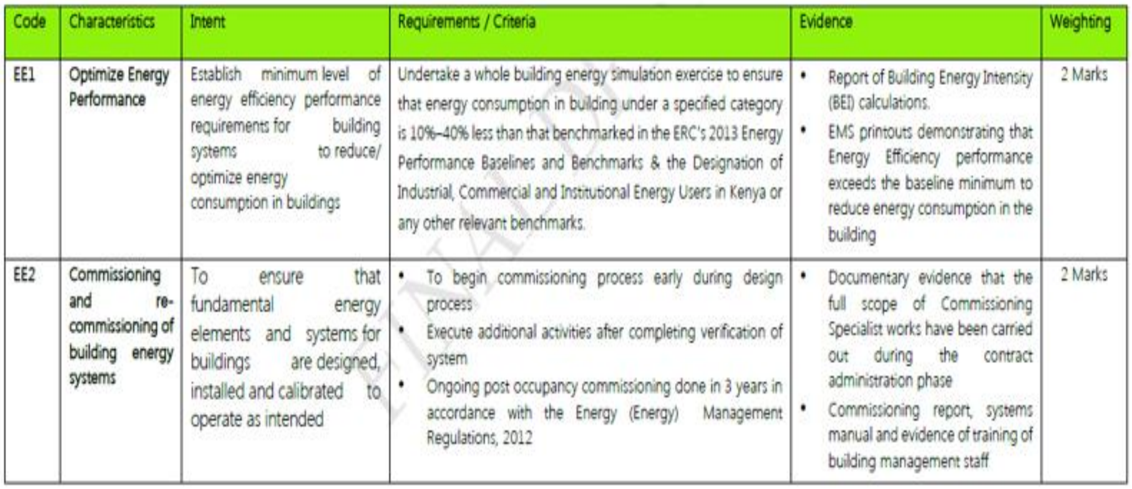
## Appendix XXVI: Air change rate for NGB2

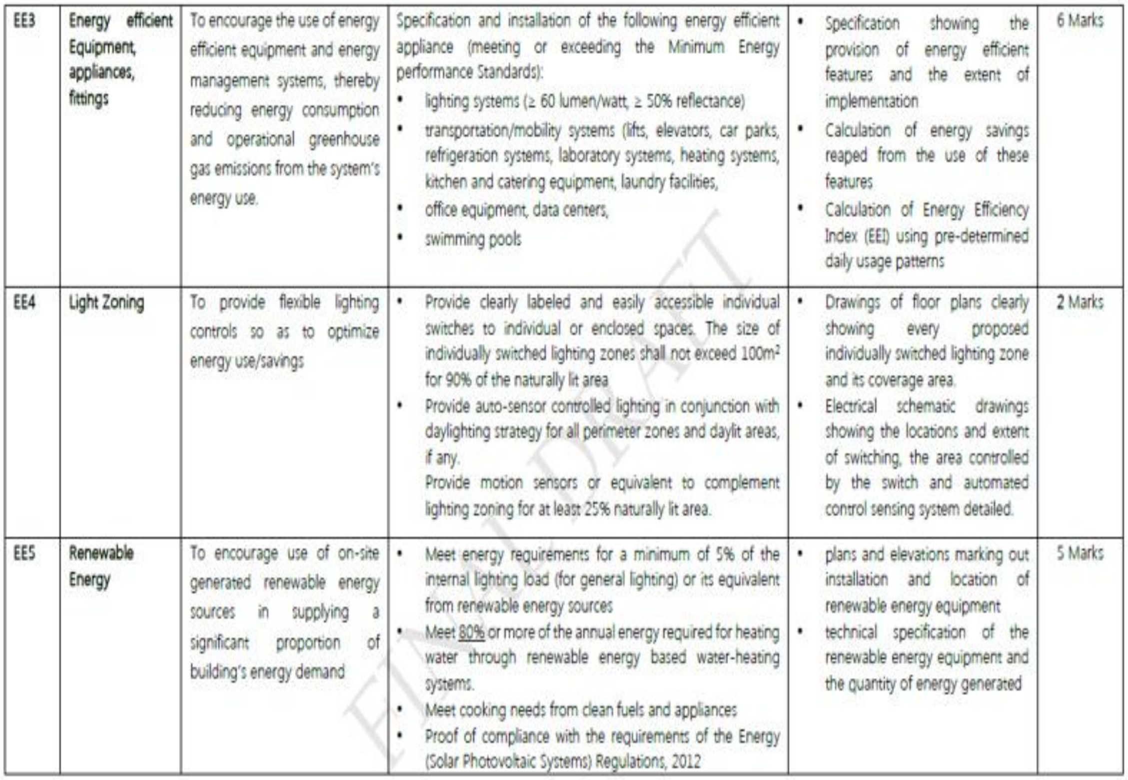


# Appendix XXVII: Air change rate for NGB2



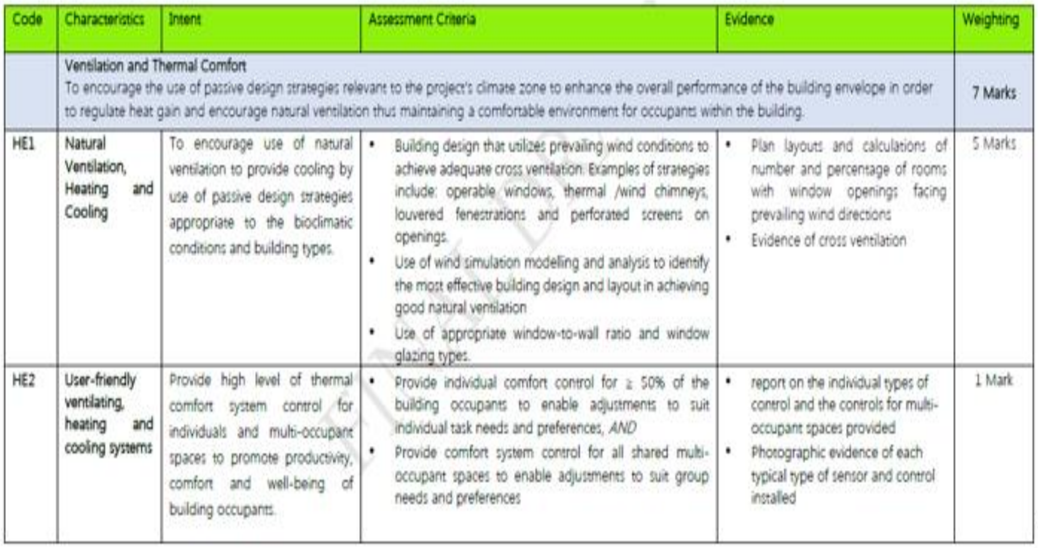
# Appendix XXVIII: GreenMark energy and renewable energy rating checklist

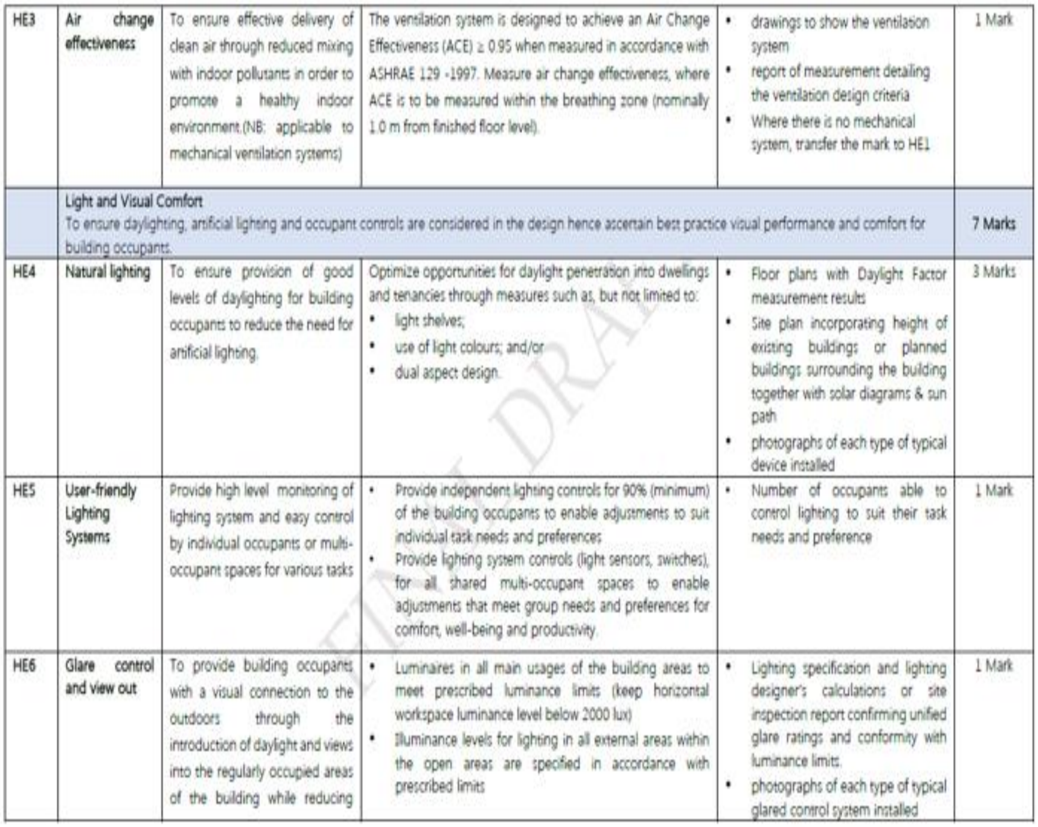




| Code | Characteristics | Intent | Requirements / Criteria | Evidence | Weighting |
|---|---|---|---|---|---|
| EE1 | **Optimize Energy Performance** | Establish minimum level of energy efficiency performance requirements for building systems to reduce/ optimize energy consumption in buildings | Undertake a whole building energy simulation exercise to ensure that energy consumption in building under a specified category is 10%–40% less than that benchmarked in the ERC's 2013 Energy Performance Baselines and Benchmarks & the Designation of Industrial, Commercial and Institutional Energy Users in Kenya or any other relevant benchmarks. | • Report of Building Energy Intensity (BEI) calculations.<br>• EMS printouts demonstrating that Energy Efficiency performance exceeds the baseline minimum to reduce energy consumption in the building | 2 Marks |
| EE2 | **Commissioning and re-commissioning of building energy systems** | To ensure that fundamental energy elements and systems for buildings are designed, installed and calibrated to operate as intended | • To begin commissioning process early during design process<br>• Execute additional activities after completing verification of system<br>• Ongoing post occupancy commissioning done in 3 years in accordance with the Energy (Energy) Management Regulations, 2012 | • Documentary evidence that the full scope of Commissioning Specialist works have been carried out during the contract administration phase<br>• Commissioning report, systems manual and evidence of training of building management staff | 2 Marks |
| EE3 | **Energy efficient Equipment, appliances, fittings** | To encourage the use of energy efficient equipment and energy management systems, thereby reducing energy consumption and operational greenhouse gas emissions from the system's energy use. | Specification and installation of the following energy efficient appliance (meeting or exceeding the Minimum Energy performance Standards):<br>• lighting systems (≥ 60 lumen/watt, ≥ 50% reflectance)<br>• transportation/mobility systems (lifts, elevators, car parks, refrigeration systems, laboratory systems, heating systems, kitchen and catering equipment, laundry facilities,<br>• office equipment, data centers,<br>• swimming pools | • Specification showing the provision of energy efficient features and the extent of implementation<br>• Calculation of energy savings reaped from the use of these features<br>• Calculation of Energy Efficiency Index (EEI) using pre-determined daily usage patterns | 6 Marks |
| EE4 | **Light Zoning** | To provide flexible lighting controls so as to optimize energy use/savings | • Provide clearly labeled and easily accessible individual switches to individual or enclosed spaces. The size of individually switched lighting zones shall not exceed $100m^2$ for 90% of the naturally lit area<br>• Provide auto-sensor controlled lighting in conjunction with daylighting strategy for all perimeter zones and daylit areas, if any.<br>Provide motion sensors or equivalent to complement lighting zoning for at least 25% naturally lit area. | • Drawings of floor plans clearly showing every proposed individually switched lighting zone and its coverage area.<br>• Electrical schematic drawings showing the locations and extent of switching, the area controlled by the switch and automated control sensing system detailed. | 2 Marks |
| EE5 | **Renewable Energy** | To encourage use of on-site generated renewable energy sources in supplying a significant proportion of building's energy demand | • Meet energy requirements for a minimum of 5% of the internal lighting load (for general lighting) or its equivalent from renewable energy sources<br>• Meet 80% or more of the annual energy required for heating water through renewable energy based water-heating systems.<br>• Meet cooking needs from clean fuels and appliances<br>• Proof of compliance with the requirements of the Energy (Solar Photovoltaic Systems) Regulations, 2012 | • plans and elevations marking out installation and location of renewable energy equipment<br>• technical specification of the renewable energy equipment and the quantity of energy generated | 5 Marks |

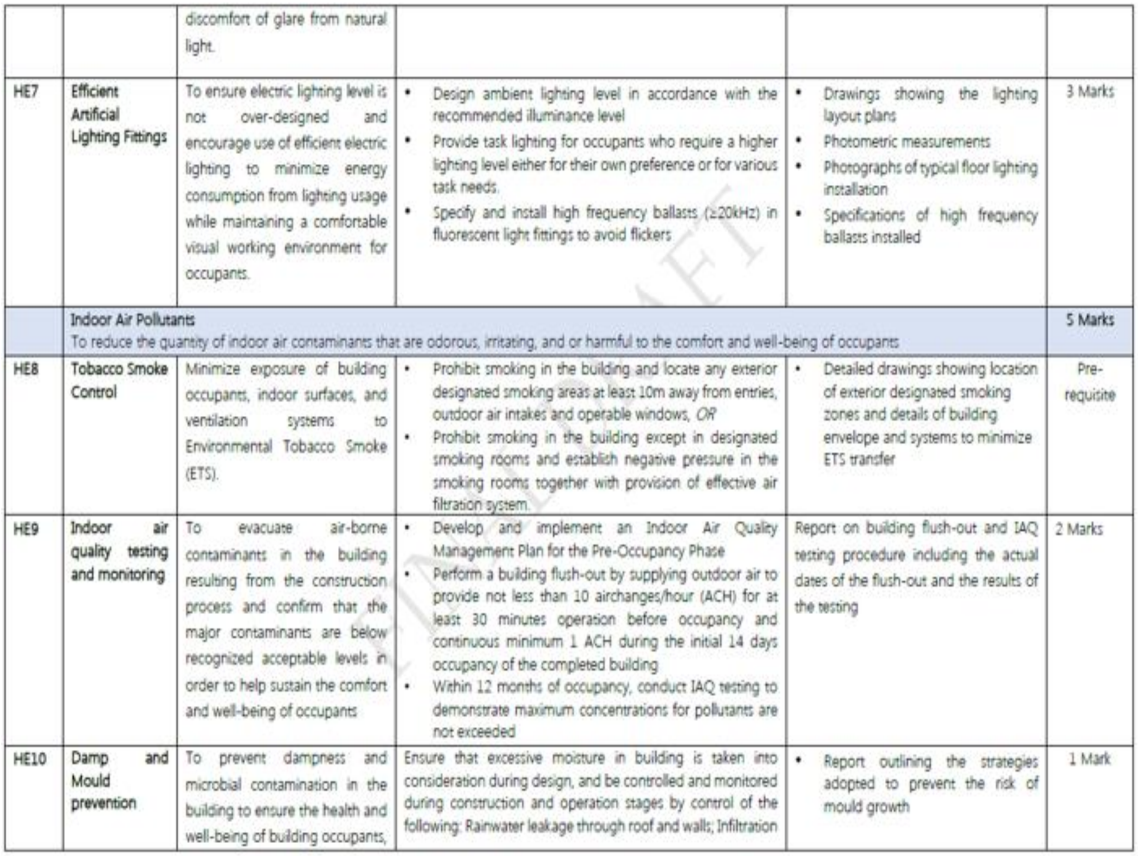
# Appendix XXIX: GreenMArk Health Indoor Environment rating checklist



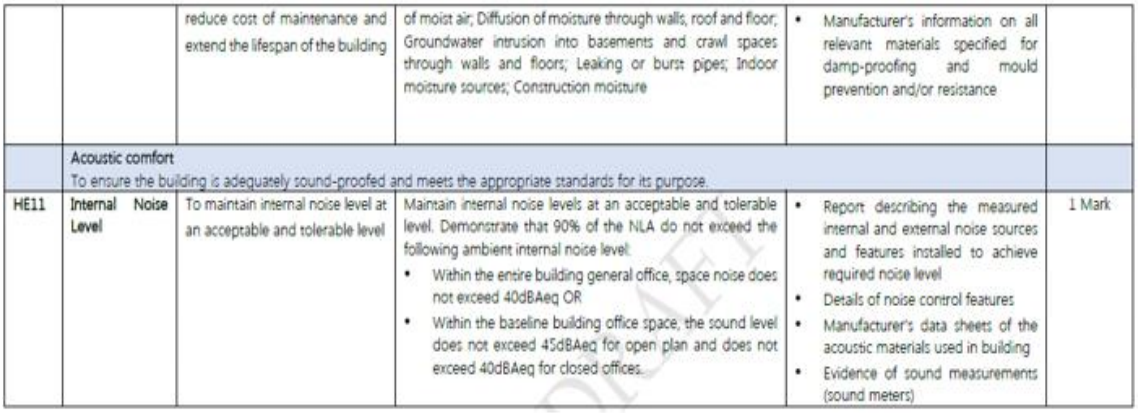


| Code | Characteristics | Intent | Assessment Criteria | Evidence | Weighting |
|---|---|---|---|---|---|
| | **Ventilation and Thermal Comfort**<br>To encourage the use of passive design strategies relevant to the project's climate zone to enhance the overall performance of the building envelope in order to regulate heat gain and encourage natural ventilation thus maintaining a comfortable environment for occupants within the building. | | | | **7 Marks** |
| HE1 | Natural Ventilation, Heating and Cooling | To encourage use of natural ventilation to provide cooling by use of passive design strategies appropriate to the bioclimatic conditions and building types. | • Building design that utilizes prevailing wind conditions to achieve adequate cross ventilation. Examples of strategies include: operable windows, thermal /wind chimneys, louvered fenestrations and perforated screens on openings.<br>• Use of wind simulation modelling and analysis to identify the most effective building design and layout in achieving good natural ventilation<br>• Use of appropriate window-to-wall ratio and window glazing types. | • Plan layouts and calculations of number and percentage of rooms with window openings facing prevailing wind directions<br>• Evidence of cross ventilation | 5 Marks |
| HE2 | User-friendly ventilating, heating and cooling systems | Provide high level of thermal comfort system control for individuals and multi-occupant spaces to promote productivity, comfort and well-being of building occupants. | • Provide individual comfort control for ≥ 50% of the building occupants to enable adjustments to suit individual task needs and preferences, *AND*<br>• Provide comfort system control for all shared multi-occupant spaces to enable adjustments to suit group needs and preferences | • report on the individual types of control and the controls for multi-occupant spaces provided<br>• Photographic evidence of each typical type of sensor and control installed | 1 Mark |
| HE3 | Air change effectiveness | To ensure effective delivery of clean air through reduced mixing with indoor pollutants in order to promote a healthy indoor environment.(NB: applicable to mechanical ventilation systems) | The ventilation system is designed to achieve an Air Change Effectiveness (ACE) ≥ 0.95 when measured in accordance with ASHRAE 129 -1997. Measure air change effectiveness, where ACE is to be measured within the breathing zone (nominally 1.0 m from finished floor level). | • drawings to show the ventilation system<br>• report of measurement detailing the ventilation design criteria<br>• Where there is no mechanical system, transfer the mark to HE1 | 1 Mark |
| | **Light and Visual Comfort**<br>To ensure daylighting, artificial lighting and occupant controls are considered in the design hence ascertain best practice visual performance and comfort for building occupants. | | | | **7 Marks** |
| HE4 | Natural lighting | To ensure provision of good levels of daylighting for building occupants to reduce the need for artificial lighting. | Optimize opportunities for daylight penetration into dwellings and tenancies through measures such as, but not limited to:<br>• light shelves;<br>• use of light colours; and/or<br>• dual aspect design. | • Floor plans with Daylight Factor measurement results<br>• Site plan incorporating height of existing buildings or planned buildings surrounding the building together with solar diagrams & sun path<br>• photographs of each type of typical device installed | 3 Marks |
| HE5 | User-friendly Lighting Systems | Provide high level monitoring of lighting system and easy control by individual occupants or multi-occupant spaces for various tasks | • Provide independent lighting controls for 90% (minimum) of the building occupants to enable adjustments to suit individual task needs and preferences<br>• Provide lighting system controls (light sensors, switches), for all shared multi-occupant spaces to enable adjustments that meet group needs and preferences for comfort, well-being and productivity. | • Number of occupants able to control lighting to suit their task needs and preference | 1 Mark |
| HE6 | Glare control and view out | To provide building occupants with a visual connection to the outdoors through the introduction of daylight and views into the regularly occupied areas of the building while reducing | • Luminaires in all main usages of the building areas to meet prescribed luminance limits (keep horizontal workspace luminance level below 2000 lux)<br>• Illuminance levels for lighting in all external areas within the open areas are specified in accordance with prescribed limits | • Lighting specification and lighting designer's calculations or site inspection report confirming unified glare ratings and conformity with luminance limits.<br>• photographs of each type of typical glared control system installed | 1 Mark |

## Appendix XXX: GreenMark Health Indoor Environment Rating Criteria



| | | | | | |
|---|---|---|---|---|---|
| | | discomfort of glare from natural light. | | | |
| HE7 | **Efficient Artificial Lighting Fittings** | To ensure electric lighting level is not over-designed and encourage use of efficient electric lighting to minimize energy consumption from lighting usage while maintaining a comfortable visual working environment for occupants. | • Design ambient lighting level in accordance with the recommended illuminance level<br>• Provide task lighting for occupants who require a higher lighting level either for their own preference or for various task needs.<br>• Specify and install high frequency ballasts (≥20kHz) in fluorescent light fittings to avoid flickers | • Drawings showing the lighting layout plans<br>• Photometric measurements<br>• Photographs of typical floor lighting installation<br>• Specifications of high frequency ballasts installed | 3 Marks |
| | **Indoor Air Pollutants**<br>To reduce the quantity of indoor air contaminants that are odorous, irritating, and or harmful to the comfort and well-being of occupants | | | | **5 Marks** |
| HE8 | **Tobacco Smoke Control** | Minimize exposure of building occupants, indoor surfaces, and ventilation systems to Environmental Tobacco Smoke (ETS). | • Prohibit smoking in the building and locate any exterior designated smoking areas at least 10m away from entries, outdoor air intakes and operable windows, *OR*<br>• Prohibit smoking in the building except in designated smoking rooms and establish negative pressure in the smoking rooms together with provision of effective air filtration system. | • Detailed drawings showing location of exterior designated smoking zones and details of building envelope and systems to minimize ETS transfer | Pre-requisite |
| HE9 | **Indoor air quality testing and monitoring** | To evacuate air-borne contaminants in the building resulting from the construction process and confirm that the major contaminants are below recognized acceptable levels in order to help sustain the comfort and well-being of occupants | • Develop and implement an Indoor Air Quality Management Plan for the Pre-Occupancy Phase<br>• Perform a building flush-out by supplying outdoor air to provide not less than 10 airchanges/hour (ACH) for at least 30 minutes operation before occupancy and continuous minimum 1 ACH during the initial 14 days occupancy of the completed building<br>• Within 12 months of occupancy, conduct IAQ testing to demonstrate maximum concentrations for pollutants are not exceeded | Report on building flush-out and IAQ testing procedure including the actual dates of the flush-out and the results of the testing | 2 Marks |
| HE10 | **Damp and Mould prevention** | To prevent dampness and microbial contamination in the building to ensure the health and well-being of building occupants, | Ensure that excessive moisture in building is taken into consideration during design, and be controlled and monitored during construction and operation stages by control of the following: Rainwater leakage through roof and walls; Infiltration | • Report outlining the strategies adopted to prevent the risk of mould growth | 1 Mark |



| | | | | | |
|---|---|---|---|---|---|
| | | reduce cost of maintenance and extend the lifespan of the building | of moist air; Diffusion of moisture through walls, roof and floor; Groundwater intrusion into basements and crawl spaces through walls and floors; Leaking or burst pipes; Indoor moisture sources; Construction moisture | • Manufacturer's information on all relevant materials specified for damp-proofing and mould prevention and/or resistance | |
| | **Acoustic comfort**<br>To ensure the building is adequately sound-proofed and meets the appropriate standards for its purpose. | | | | |
| HE11 | **Internal Noise Level** | To maintain internal noise level at an acceptable and tolerable level | Maintain internal noise levels at an acceptable and tolerable level. Demonstrate that 90% of the NLA do not exceed the following ambient internal noise level:<br>• Within the entire building general office, space noise does not exceed 40dBAeq OR<br>• Within the baseline building office space, the sound level does not exceed 45dBAeq for open plan and does not exceed 40dBAeq for closed offices. | • Report describing the measured internal and external noise sources and features installed to achieve required noise level<br>• Details of noise control features<br>• Manufacturer's data sheets of the acoustic materials used in building<br>• Evidence of sound measurements (sound meters) | 1 Mark |